

Ad-hoc Wireless Networking for Supporting On-Site Communication

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ABSTRACT

Ad-hoc Wireless Networking for Supporting On-Site Communication

Linchuan Yang

Ad-hoc networks are self-organized wireless networks. They have the potential to be widely used in emergency salvation, construction sites, and military fields. However, the research about the efficient usage of ad-hoc networking in engineering applications is still limited. In this research, a new approach for investigating problems related to deploying ad-hoc wireless networks for supporting on-site communication and collaboration is proposed. Several modes of communication which are common in on-site applications are considered including location information, text messaging, voice and video communications, and file transmission. A prototype system is implemented for testing these modes based on available ad-hoc network protocols and using mobile devices. In addition, in order to verify our proposed approach, several tests are designed and implemented to demonstrate the usefulness of the prototype system. The results from the tests showed that our prototype system is applicable for ad-hoc wireless networks. Furthermore, a new protocol based on clustering to improve data accessibility in ad-hoc networks is tested using a simulation tool to study its performance under different scenarios. The simulation results showed the impact of the area size, wireless range, number of nodes, and node speed on data accessibility.

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LIST OF ABBREVIATIONS

| Abbreviation | Description |
|---------------|--|
| 2D | Two-dimensional |
| 2G | Second-generation |
| 3D | Three-dimensional |
| 3G | Third-generation |
| AODV | Ad-hoc on Demand Distance Vector |
| AMPS | Advanced Mobile Phone Service |
| AP | Access Point |
| API | Application Programming Interface |
| BSS | Basic Service Set |
| BWA | Broadband Wireless Access |
| CBRA | Cluster Based Replica Allocation |
| CDMA | Code-Division Multiple Access |
| CDS | Connected Dominating Set |
| CSMA | Carrier Sense Multiple Access |
| DAFN | Dynamic Access Frequency and Neighborhood |
| D-AMPS | Digital-Advanced Mobile Phone Service |
| DCG | Dynamic Connectivity based Grouping |
| DECT | Digital Enhanced Cordless Telecommunications |
| DS | Dominating Sets |
| DSDV | Destination Sequenced Distanced Vector |
| DSR | Dynamic Source Routing |
| GPRS | General Packet Radio Service |
| GPS | Global Positioning System |
| GSM | Global System for Mobile Communications |
| IBSS | Independent Basic Service Set |
| JMF | Java Media Framework API |
| LAN | Local Area Network |
| LCC | Least Cluster Change |
| LIC | Lowest ID Clustering |
| MAC | Medium Access Control |
| MANET | Mobile Ad-hoc Network |
| MASC | Mobile Ad-hoc Space for Collaboration |
| MNR | Mesh Network Radio |
| PCS | Personal Communications Service |

| | |
|--------------|---|
| PDA | Personal Digital Assistant |
| QoS | Quality of Service |
| RERR | Route Error |
| RREP | Route Reply |
| RREQ | Route request |
| RTP | Real-time Transport Protocol |
| SAF | Static Access Frequency |
| SMS | Short Message Service |
| SSID | Service Set Identifier |
| TDMA | Time Division Multiple Access |
| TTL | Time To Live |
| UAVs | Unmanned Aerial Vehicles |
| UHF | Ultra-high-frequency |
| VoIP | Video and voice over IP |
| VR | Virtual Reality |
| VVPN | Voice Virtual Private Network |
| WCA | Weighted Cluster Algorithm |
| WEP | Wired Equivalent Privacy |
| WiMAX | Worldwide Interoperability for Microwave Access |
| WLAN | Wireless Local Area Networks |
| WME | Wireless Multimedia Extension |
| WMM | Wi-Fi Multimedia |
| WNC | Wireless Network Cells |
| ZRP | Zone Routing Protocol |

CHAPTER 1 INTRODUCTION

1.1 GENERAL BACKGROUND

Efficient collaboration among team members working in the field, such as inspection teams, search and rescue teams after a disaster, and troops in the battle, is important to realize the intended tasks. Real-time communication is necessary for those field workers to enhance their collaborative efforts. Nowadays, several technologies are used on site, such as cellular/mobile phones, digital enhanced cordless telecommunications (DECT), voice virtual private networks (VVPN), wired local-area networks (LAN), and satellite telecommunications. However, these technologies have some disadvantages, which may affect the work on-site. Furthermore, all of the above technologies need some type of infrastructure (e.g., wiring, routers, etc.). If the available infrastructure is damaged because of natural or man-made disasters, all the on-site communications will stop, which will lead to extra losses and, in some cases, additional casualties. Consequently, a technique which does not need any infrastructures, and which is economical and efficient, is needed.

Ad-hoc networking is an attractive solution for this problem because it allows field workers using portable devices to communicate and keep in touch with each other when they are performing their tasks. Many kinds of devices could be used as clients in an ad-hoc wireless network, such as notebooks, tablet PCs, and PDAs. These devices have wireless adapters with different standards (mainly IEEE 802.11a, b, and g), which include encryption schemes to make the ad-hoc network as secure as the wired LAN.

Several research projects considered the usage of wireless networks to support on-site communications, and some of them discussed a new approach to use ad-hoc networking to support effective collaboration among first response organizations with high performance of data accessibility. However, the research about the efficient usage of ad-hoc networking in engineering applications is still limited. On the other hand, research about new protocols aiming to improve the ad-hoc network performance is progressing using several clustering and replication techniques. However, these protocols need careful testing from the point-of-view of the engineering applications.

1.2 RESEARCH OBJECTIVES

This research aims to investigate the applicability of ad-hoc wireless networking for supporting on-site communication. The research includes two parts: a prototype system for supporting different communication methods using ad-hoc wireless networks and an ad-hoc clustering simulation. The research has the following objectives:

- (1) Defining the basic modes of communication which are common in on-site applications;
- (2) Implementing and testing these modes using a prototype system based on available ad-hoc network protocols and using mobile devices; and
- (3) Simulating the performance of a new protocol based on clustering to improve data accessibility using different scenarios.

1.3 THESIS ORGANIZATION

This research will be presented as follows:

Chapter 2 Literature Review: This chapter presents most of the current wireless methods for communication and collaboration. Many routing protocols for ad-hoc networks are introduced, and a new approach of Cluster-based Replica Allocation (CBRA) is reviewed. Furthermore, many popular simulation tools are compared. In addition, several test-beds based on ad-hoc wireless networks are reviewed.

Chapter 3 Proposed approach: This chapter has two parts. In the first part, a system design is presented for testing ad-hoc wireless communications. In order to test this system, two types of tests are used with different routing solutions. In the second part, simulation scenarios of a new clustering algorithm based on CBRA protocol to improve data accessibility are presented.

Chapter 4 Implementation and testing: This chapter discusses the implementation details of the proposed system called “*Ad-hoc Messenger*”, the testing of this system, and the simulation results of the CBRA protocol.

Chapter 5 Summary, Conclusions, and Future work: This Chapter summarizes the presented research work, highlights the contributions, and suggests recommendations for future research.

CHAPTER 2 LITERATURE REVIEW

2.1 WIRELESS NETWORKS

Wireless networks follow several standards such as IEEE 802.11. A basic such wireless network consists of multiple stations communicating (enabling file sharing, printer sharing, Internet connection, etc.) with radios that broadcast in either the 2.4 GHz or 5 GHz band. While the term wireless network may technically be used to refer to any type of network that is wireless, the term is most commonly used to refer to a telecommunications network whose interconnection between nodes is implemented without the use of wires, such as a computer network. Wireless telecommunications networks are generally implemented with some type of information transmission system that uses electromagnetic waves, such as radio waves, for the carrier and this implementation usually takes place at the physical layer of the network (Search Mobile Computing, 2007). The following paragraphs briefly introduce examples of wireless networks.

(1) Wireless LAN

A wireless LAN (Local Area Network) or WLAN is one in which a mobile user can connect to a LAN through a wireless radio connection or infrared signals instead of traditional network cabling over short distances. WLAN extends an existing wired LAN by attaching an access point (AP) to the edge of the network. Clients connect with the AP using a wireless network adapter that has the same function of a traditional Ethernet adapter. The backbone network of WLAN usually uses cables, with one or more wireless

AP connecting the wireless users to the wired network. The area of WLAN may range from a single room to an entire campus (About.com, 2007).

Wi-Fi is a term for certain types of WLAN that use specifications in the 802.11 family. The term Wi-Fi was created by an organization called the Wi-Fi Alliance, which oversees tests that certify product interoperability. A product that passes the alliance tests is given the label "Wi-Fi certified" (a registered trademark). Originally, Wi-Fi certification was applicable only to products using the 2.4 GHz 802.11b standard. Today, Wi-Fi can apply to products that use any 802.11 standard. The particular specification under which a Wi-Fi network operates is called the "flavor" of the network. Wi-Fi has gained acceptance in many businesses, agencies, schools, and homes as an alternative to a wired LAN. Many airports, hotels, and fast-food facilities offer public access to Wi-Fi networks. These locations are known as hot spots, most of them are free (Wi-Fi, 2003).

(2) WiMAX (Worldwide Interoperability for Microwave Access)

WiMAX is a wireless industry coalition whose members work to advance IEEE 802.16 standards for broadband wireless access (BWA) networks. WiMAX was formed in April 2001, and until now, it is expected to provide up to 15 Mbps of capacity within a typical cell radius deployment of up to three kilometers. WiMAX aims to provide wireless data over long distances, in a variety of different ways, from point to point links to full mobile cellular type access. Members of the WiMAX forum include Airspan, Alvarion, Analog Devices, Aperto Networks, Ensemble Communications, Fujitsu, Intel, Nokia, OFDM Forum, Proxim, and Wi-LAN. WiMAX Forum Certified™ systems can be expected to

deliver capacity of up to 40 Mbps per channel, for fixed and portable access applications (WiMAX forum, 2007).

(3) Fixed Wireless Data

Fixed wireless data is a type of wireless data network that can be used to connect two or more buildings together in order to extend or share the network bandwidth without physically wiring the buildings together. Fixed wireless devices usually derive their electrical power from the utility mains, unlike mobile wireless or portable wireless which tend to be battery-powered. Although mobile and portable systems can be used in fixed locations, efficiency and bandwidth are compromised compared with fixed systems (SR Telecom, 2007).

(4) Digital mobile telephony systems

Several types of digital mobile telephony systems are available, such as Global System for Mobile Communications (GSM), General Packet Radio Service (GPRS), Code-Division Multiple Access (CDMA), and Digital Enhanced Cordless Telecommunications (DECT).

GSM is a digital mobile telephony system that is widely used in Europe and other 200 countries of the world. It digitizes and compresses data, then sends it down a channel with two other streams of user data, each in its own time slot. GSM uses a variation of time division multiple access (TDMA) and is the most widely used of the three digital wireless telephony technologies (TDMA, GSM, and CDMA). It operates at either the 900 MHz or 1800 MHz frequency band. The network of GSM is divided into three major

systems: the switching system, the base station system, and the operation and support system (Search Mobile Computing, 2007).

GPRS is a mobile data service available to users of GSM and IS-136 mobile phones. It is a packet-based wireless communication service that supports data rates from 56 up to 114 Kbps and continuous connection to the Internet for wireless devices, such as mobile phone and mobile computer users. GPRS is based on GSM communication and complements existing services, such as circuit-switched cellular phone connections and the Short Message Service (SMS). The higher data rates allow GPRS users to take part in video conferences and interact with multimedia web sites using wireless mobile devices (Search Mobile Computing, 2007).

CDMA refers to any of several protocols used in so-called second-generation (2G) and third-generation (3G) wireless communications. The technology is used in ultra-high-frequency (UHF) cellular telephone systems in the 800-MHz and 1.9-GHz bands. In order to carry many conversations over one frequency, CDMA sends all communications in groups of bits mixed altogether, but tags each group belonging to a specific communication, with a different code. Therefore, at the other end, each communication can be rebuilt in the correct order based on the unique codes attached to certain groups of bits (Wi-Fi planet, 2007).

DECT is a digital wireless telephone technology that is expected to make cordless phones much more common in both businesses and homes in the future. Formerly called the

Digital European Cordless Telecommunications standard because it was developed by European companies, DECT's present name reflects its global acceptance. Like GSM, DECT uses TDMA to transmit radio signals to phones. Whereas GSM is optimized for mobile travel over large areas, DECT is designed especially for a smaller area with a large number of users, such as in cities and corporate complexes (Parks Associates, 2007).

2.2 AD-HOC NETWORKS

An ad-hoc network is a WLAN or other small network, especially one with wireless or temporary plug-in connections, in which some of the network devices are part of the network only for the duration of a communication session or, in the case of mobile or portable devices, while in some close proximity to the rest of the network. In Latin, ad-hoc literally means "for this," further meaning "for this purpose only," and thus usually temporary. It is a peer-to-peer wireless network that transmits from computer to computer without the use of a central base station (access point). The term has been applied to future office or home networks in which new devices can be quickly added, for example, Wi-Fi, and Bluetooth technology in which devices communicate with the computer and other devices using wireless transmission (Search Mobile Computing, 2007).

2.2.1 CHARACTERISTICS OF AD-HOC NETWORKS

The main characteristics of ad-hoc networks are (ARC Communications Research Network, 2006):

- Do not need complex pre-configuration, the network configuration and management could be automatic and dynamic.
- Do not need any infrastructure, all the nodes can move randomly within the range of wireless signal.
- Multi-hop routing: each node in the network works as a router.
- Low-cost devices: any mobile devices that have power and CPU processing, e.g. laptops, PDAs and mobile phones can be used in ad-hoc networks.
- Resource limited wireless communications: e.g. all nodes should communicate with the bandwidth of IEEE 802.11 b (11 Mbps) or 802.11 g (54 Mbps).
- Potentially large networks: e.g. a network of sensors may comprise thousands or even tens of thousands of mobile nodes.

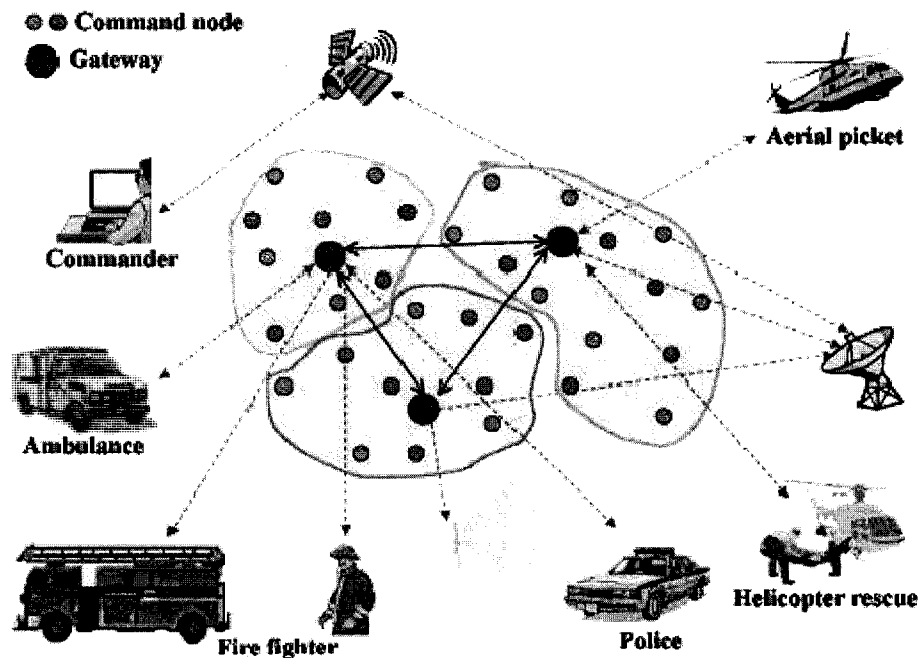


Figure 2.1 Ad-hoc Networks (WMC, 2006)

2.2.2 APPLICATIONS OF AD-HOC NETWORKS

The following fields and scenarios could be considered to use ad-hoc networks:

- Construction site: In a construction site, there might be no available communication infrastructure. Ad-hoc networks could support the on-site communication and collaboration.
- Emergency salvation: In a man-made or natural disaster, the current communication infrastructure could be damaged. Ad-hoc networks could act as the contingency solution for salvation teams (Figure 2.1).
- Sensor networks: Small sensor devices can be attached to animals or other strategic locations that collectively, to monitor habitats and environmental conditions.
- Automotive networks: The pre-installed ad-hoc network devices in vehicles can provide the drivers with information about road conditions, congestions, and accident-ahead warnings, helping to optimise traffic flow.
- Military applications: Armed forces can create a tactical ad-hoc network in unfamiliar territory for communications and distribution of situational awareness information.

2.2.3 SECURITY IN AD-HOC NETWORKS

(1) Link Level Security

In a wireless environment, the links are susceptible to attacks where eavesdropper can easily spoof the on-going communication. As there is no protection like firewalls or access control in ad-hoc network, any node can become vulnerable to attacks coming

from any direction or from any node. The results of such attacks include spoofing of the node's identity, tampering with node's credentials, leaking of confidential information or impersonating node. These types of attacks can easily compromise the basic security aspects like confidentiality, integrity, and availability and privacy of the node. The possible solution for link level security could be installing firewalls on each node (Aziz, 2007).

(2) Secure Routing

The routing part of an ad-hoc network is more vulnerable to attacks because each device acts as a relay. Any tampering with routing information can compromise the whole network. An attacker can insert rogue information within routing information or introduce denial-of-service type attack by replaying old logged information. Also, compromised node can route malicious information to other nodes, which can cause serious damage. Selecting suitable routing protocols could reduce the potential threaten to the ad-hoc networks (Vinayakray-Jani, 2002).

2.2.4 QUALITY OF SERVICE (QoS) IN AD-HOC NETWORKS

QoS is a guarantee that the network can satisfy a set of predetermined service performance constraints for user in terms of the end-to-end delay statistics, available bandwidth, probability of packet loss, and so on. QoS for a network is measured in terms of guaranteed amount of data which a network transfers from one place to another in a given time slot. In ad-hoc networks, the QoS could be measured by the quality of the delivery of real-time communications such as audio and video. The size of the ad-hoc network is directly related to the QoS of the network. If the size of the mobile ad-hoc

networks (MANETs) is large, it might make the problem of network control extremely difficult. Communication in MANETs between two participating nodes can be seen as a complex end-to-end channel that changes routes with time. QoS support in ad-hoc networks encompasses issues at the application layer, transport layer, network layer, medium access control (MAC) layer, and physical layer of the network infrastructure (Computing unplugged, 2007).

2.2.4.1 QoS METRICS

QoS is usually defined as a set of service requirements that needs to be met by the network while transporting a packet stream from a source to its destination. The network is expected to guarantee a set of measurable specified service attributes to the user in terms of end-to-end delay statistics, bandwidth, probability of packet loss, delay variance (jitter), etc. Energy efficiency and service coverage are two other QoS attributes that are more specific to wireless ad-hoc networks due to the limited battery source (Prasant, 2004).

The QoS metrics could be concave or additive. Bandwidth is concave in the sense that end-to-end bandwidth is the minimum of all the links along the path. Delay and delay jitter are additive. The end-to-end delay (jitter) is the accumulation of all delays (jitters) of the links along the path. Furthermore, QoS metrics could be defined in terms of one of the parameters or a set of parameters in varied proportions. Multi-constraint QoS aims to optimize multiple QoS metrics while provisioning network resources, and is a complex problem. It has been proved that if QoS contains at least two additive metrics then the QoS routing is an NP-complete (NP means non-deterministic polynomial time) problem.

Thus heuristic algorithms are usually developed for multi-constraints QoS routing (Li, 2006).

2.2.4.2 ISSUES OF QoS

The following are some of the major issues of QoS (Li, 2006):

- **Unpredictable link properties:** Wireless media is very unpredictable. Packet collision is intrinsic to wireless network. Signal propagation faces difficulties such as signal fading, interference, and multi path cancellation. All these properties make measures such as bandwidth and delay of a wireless link unpredictable.
- **Node mobility:** Mobility of the nodes creates a dynamic network topology. Links will be dynamically formed when two nodes come into the transmission range of each other and are torn down when they move out of range.
- **Limited battery life:** Mobile devices generally depend on finite battery sources. Resource allocation for QoS provisioning must consider residual battery power and rate of battery consumption corresponding to resource utilization. Thus, all the techniques for QoS provisioning should be power-aware and power efficient.
- **Hidden and exposed terminal problems:** In a MAC layer with the traditional carrier sense multiple access (CSMA) protocol, multi-hop packet relaying introduces the “hidden terminal” and “exposed terminal” problems. The hidden terminal problem happens when signals of two nodes, say A and B, that are out of each other's transmission ranges collide at a common receiver, say node C. With the same nodal configuration, an exposed terminal problem will result from a scenario where node B attempts to transmit data (to someone other than A or C) while node C is transmitting

to node A. In such a case, node B is exposed to the transmission range of node C and thus defers its transmission even though it would not interfere with the reception at node A.

- **Route maintenance:** The dynamic nature of the network topology and the changing behavior of the communication medium make the precise maintenance of network state information very difficult. Thus, the routing algorithms in MANETs have to operate with inherently imprecise information. Furthermore, in ad-hoc networking environments, nodes can join or leave at any time. The established routing paths may be broken even during the process of data transfer. Thus, the need arises for maintenance and reconstruction of routing paths with minimal overhead and delay.
- **QoS-aware routing** would require reservation of resources at the routers (intermediate nodes). However, with the changes in topology the intermediate nodes also change, and new paths are created. Thus, reservation maintenance with updates in the routing path becomes cumbersome.
- **Security:** Security can be considered a QoS attribute. Without adequate security, unauthorized access and usage may violate QoS negotiations. The nature of broadcasts in wireless networks potentially results in more security exposure. The physical medium of communication is inherently insecure, so we need to design security-aware routing algorithms for MANETs.

2.3 ROUTING PROTOCOLS IN AD-HOC NETWORKS

One of the main characteristics of ad-hoc networks is the capability of each node to act as a router. These routing functions are supported by the routing protocols of the network layer. As the topology of the network is dynamic, it is a big challenge to design routing protocols that can cope up with the changing topology. A path in an ad-hoc network found from host to destination may not remain alive after few moments. To deal with such situations, researchers have developed routing protocols for ad-hoc networks that can be classified as proactive, reactive and hybrid (Lee et al., 2007).

(1) Proactive Protocols

Proactive protocols maintain routes to all nodes including nodes to which no packets are scheduled for, e.g., destination sequenced distanced vector (DSDV) protocol. These protocols have high overhead in maintaining and updating the whole topology information periodically. When a packet transmission request is received, the updated information about routes is searched in the source nodes' routing table and the packet is transmitted based on the route information available. In case the entry for a route to destination is not available in the routing table, network wide broadcast is initiated to find the route.

(2) Reactive Protocols

A reactive protocol, on the contrary, establishes routes on demand. Examples of this protocol class are ad-hoc on demand distance vector (AODV) and dynamic source routing (DSR). Due to on-demand route search, these protocols introduce delay in packet

delivery. For these protocols whenever a packet has to be sent from source to destination, route request (RREQ) messages are broadcasted by the source node. The very first of RREQ message received by destination node prompts it to send the route reply (RREP) message on the same path it received the RREQ. This process in association with some other acknowledgement and hello messages allows route discovery for this class of protocols.

(3) Hybrid Protocols

The third class of ad-hoc routing protocols, the hybrid protocols, combines the best of proactive and reactive protocols, e.g., Zone Routing Protocol (ZRP). It uses distance-vectors to determine the best paths to destination networks, and report routing information only when there is a change in the topology of the network.

2.4 IEEE 802.11 STANDARDS

The IEEE 802.11 standards are widely used for wireless networks. These standards support communication in two modes: infrastructure mode and ad-hoc mode. 802.11 networks are organized in two ways: in a Basic Service Set (BSS) one station acts as a master with all the other stations associating to it; this is termed infrastructure mode and the master station is termed an access point (AP). In BSS mode all communication passes through the AP. In the second form of networks, there is no master station. This form of networks is termed an Independent Basic Service Set (IBSS) and is commonly known as an ad-hoc network (IEEE, 2006).

IEEE 802.11 networks were first created in the 2.4 GHz band using protocols defined by the IEEE 802.11b standard. These specifications include the operating frequencies, MAC layer characteristics including framing and transmission rates (communication can be done at various rates). Later the IEEE 802.11a standard defined operation in the 5 GHz band, including different signaling mechanisms and higher transmission rates. Still later the 802.11g standard was defined to enable the use of 802.11a signaling and transmission mechanisms in the 2.4 GHz band in such a way as to be backwards compatible with 802.11b networks (IEEE, 2006).

IEEE 802.11 standards have provided some basic security mechanisms to make ad-hoc networks less of a potential threat. For example, 802.11 access points (or sets of access points) can be configured with a service set identifier (SSID). Additional security is provided through the 802.11 specifications through the Wired Equivalent Privacy (WEP) algorithm. WEP provides 802.11 with authentication and encryption services. The WEP algorithm defines the use of a 40-bit secret key for authentication and encryption and many IEEE 802.11 implementations also allow 104-bit secret keys. This algorithm provides mostly protection against eavesdropping and physical security attributes comparable to a wired network (IEEE, 2006).

Other than the above protocol standards, the other important standard to be aware of is 802.11e. This defines protocols for deploying multi-media applications such as streaming video and voice over IP (VoIP) in an 802.11 network. The 802.11e has a precursor

specification termed Wireless Multimedia Extensions (WME) (and now Wi-Fi Multimedia (WMM)) that has been defined by an industry group as a subset of 802.11e that can be implemented to enable multi-media applications while waiting for the final ratification of 802.11e. The most important thing to understand about 802.11e and WME/WMM is that they enable prioritized traffic use of a wireless network through Quality of Service (QoS) protocols and enhanced media access protocols. Proper implementation of these protocols enable high speed bursting of data and prioritized traffic flow (IEEE, 2006).

2.5 NETWORK SIMULATION

Network simulation is a technique where a program manipulates simulated entities, such as hosts and routers, in order to determine their behavior under various conditions. A simulator is a device, computer program or system used during software verification, which behaves or operates like a given system when provided with a set of controlled inputs (IEEE, 2006). A key feature of network design is the estimation of the performance of a proposed network design. In the case of realistic network topologies and network applications, performance estimation is a difficult problem. As a result, a number of powerful simulators have been developed that are capable of attacking these problems. Three of the well-known simulators are Ns2, OPNET, and GloMoSim.

(1) NS2

Ns2 is a free and open-source network simulator. It is a discrete event simulator targeted at networking research. Ns2 provides substantial support for simulation of TCP, routing, and multicast protocols over wired and wireless (local and satellite) networks. Ns2 covers a very large number of applications, protocols, network types, network elements and traffic models. Ns2 is based on two languages: an object oriented simulator, written in C++, and a OTcl (an object oriented extension of Tcl) interpreter, used to execute user's command scripts (USC, 2005).

Characteristics of NS2:

- The compiled C++ hierarchy allows it to achieve efficiency in the simulation and faster execution time.
- Ns2 is a discrete event simulator, where the advance of time depends on the timing of events which are maintained by a scheduler.
- Tcl allows a fast development, provides a graphic interface, is compatible with many platforms, and is flexible for integration (USC, 2005).

Because of its availability and the above characteristics, Ns2 is used in this research.

(2) OPNET

OPNET is the industry's leading simulator specialized in network research and development (OPNET technologies, 2007). It allows users to design and study communication networks, devices, protocols, and applications with great flexibility. It provides a graphical editor interface to build models for various network entities from

physical layer modulator to application processes. All the components are modeled in an object-oriented approach which gives intuitive easy mapping to real systems. OPNET simulations are usually created and configured using a mix of graphical editors, state-diagrams and C++. The OPNET's discrete event engine for network simulations is the fastest and most scalable commercially available solution. It usually takes just a few minutes to complete simulations of most lab experiments (OPNET technologies, 2007).

(3) GloMoSim

GloMoSim is a scalable simulation environment for wireless and wired network systems. It is being designed using the parallel discrete-event simulation capability provided by Parsec. GloMoSim currently supports protocols for a purely wireless network. GloMoSim allows the simulation of wired and wireless networks, and it is configured through a configuration file and provides a reasonable number of readily available protocols, radio layers, etc. (UCLA Parallel Computing Laboratory, 2007).

2.6 DATA REPLICATION AND CLUSTERING IN AD-HOC NETWORKS

2.6.1 DATA REPLICATION IN AD-HOC NETWORKS

In ad-hoc networks, since the nodes move freely, network divisions happen frequently, which leads to lower data accessibility than that in wired networks. Therefore, an efficient method that can backup the important data in ad-hoc networks is needed (Jiang et al., 1999). In order to solve this problem, effective replica allocation can be used. Several replica allocation methods have been proposed. such as Static Access Frequency

(SAF) method, Dynamic Access Frequency and Neighborhood (DAFN) method, and Dynamic Connectivity based Grouping (DCG) method (Hara, 2001).

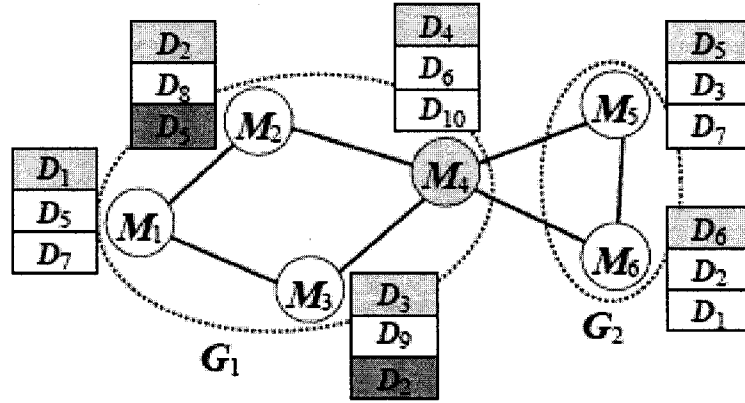


Figure 2.2 DCG Method
(Hara, 2001)

The DCG method extended the SAF and DAFN methods; it divides the nodes into larger groups based on biconnected components (Aho et al., 1974), and checks the replicas between groups. Figure 2.2 shows the detailed method: First, at the relocation period, each node broadcasts its identifier and information on data item access frequencies. Second, the algorithm separate the nodes into groups based on biconnected components. Third, each group calculates the sum of access frequencies of each data item. Fourth, in the order of the access frequencies of the group, replicas of the original data in other groups are allocated to the node which has higher access frequency of the data until memory space of all nodes in the group becomes full. Finally, if there is free memory space left in the group, replicas of the original data that in this group are allocated in the order of access frequencies until the memory space is full. The DCG method shares replicas in larger groups, so the network has higher stability. However, it uses lot of time

to exchange information among nodes and calculate access frequencies, so the overhead and traffic are higher than other replication methods (Hara, 2001).

2.6.2 CLUSTERING IN AD-HOC NETWORKS

Large number of nodes in the same network could reduce the efficiency of the network. Therefore, in order to improve the scalability of the network, it should be divided into clusters, with every cluster having no more than 50 nodes (Xu and Hischke, 2003). The clusters in the MANETs are groups of mobile nodes. These nodes move within or among clusters with some special rules. Furthermore, nodes in the same cluster are assigned different status and functions, such as cluster heads, cluster member, and gateway. The current clustering methods in MANETs could be divided into the following categories:

(1) DS-based clustering

This clustering scheme tries to find a Dominating Set (DS) or Connected Dominating Set (CDS) to reduce the number of nodes participating in route search or routing table maintenance. In this scheme, routing is done through DS or CDS (Yu and Chong, 2005).

(2) Low-maintenance clustering

This clustering scheme provides a cluster infrastructure for upper layer applications with little cluster maintenance cost (Yu and Chong, 2005). It tries to eliminate the control overhead for clustering by constructing and maintaining cluster architecture based on data traffic forwarding (Kwon et al., 2003). Examples of low-maintenance clustering are: LCC

(Least Cluster Change) (Chiang and Gerla, 1997), LIC (Lowest ID Clustering) (Ephremides et al., 1987).

(3) Mobility-aware clustering

This clustering scheme utilizes the mobility behavior of mobile nodes for cluster construction and maintenance, and assigns mobile nodes with low relative speed to the same cluster to tighten the connection within the cluster. Therefore, the re-affiliation and re-clustering rate can be reduced (Yu and Chong, 2005).

(4) Energy-efficient clustering

This clustering scheme avoids unnecessary energy consumption and balances energy consumption for mobile nodes in order to prolong the lifetime of mobile nodes and the whole network (Yu and Chong, 2005). Energy consumption of mobile nodes could lead to network partition and communication interruption. Therefore, it is important to balance the energy consumption among the whole network.

(5) Load-balancing clustering

This clustering scheme attempts to limit the number of mobile nodes in each cluster to a defined range in order to keep all clusters with the similar size (Yu and Chong, 2005). This method has upper and lower limits on the number of mobile nodes that a cluster can deal with. Thus, the network loads can be more averagely distributed in each cluster.

(6) Combined-metrics-based clustering

This cluster scheme considers multiple metrics, such as, cluster size, mobility speed, and battery energy in cluster configuration, and adjusts their weighting factors for different application scenarios (Yu and Chong, 2005). This method aims to elect the most suitable cluster head in a local area, and do not give preference to mobile nodes with certain attributes, such as lowest ID or highest node degree. Example of combined-metrics-based is: On-Demand WCA (Weighted Cluster Algorithm) (Chatterjee et al., 2000).

2.6.3 CLUSTER BASED REPLICA ALLOCATION (CBRA)

As reviewed in Section 2.6.1, the DCG method divides the nodes into larger groups based on biconnected components (Aho et al., 1974), and checks the replicas between groups. However, in real ad-hoc networks, all nodes move randomly, and it is possible that more than one node disappear at the same time. If these nodes were in important positions in the same group (For example, node 8, 9, 10, 11 in group II in Figure 2.3), then the new partitions will happen.

Efficient clustering and routing protocols are important parts of the design of an ad-hoc network (Macker, 1997). Clustering saves resources which may result from transmission collisions. Clustering also improves routing performance through cluster heads and gateway clients; therefore restricting the routing events to a set of clients. In addition, the cluster structure makes an ad-hoc network appears smaller and stable from the point of view of each mobile client because only clients belonging to the same cluster need to

update information. In order to avoid the problem in Figure 2.3, Mahboob (2005) introduced a new replication method, CBRA, based on clustering.

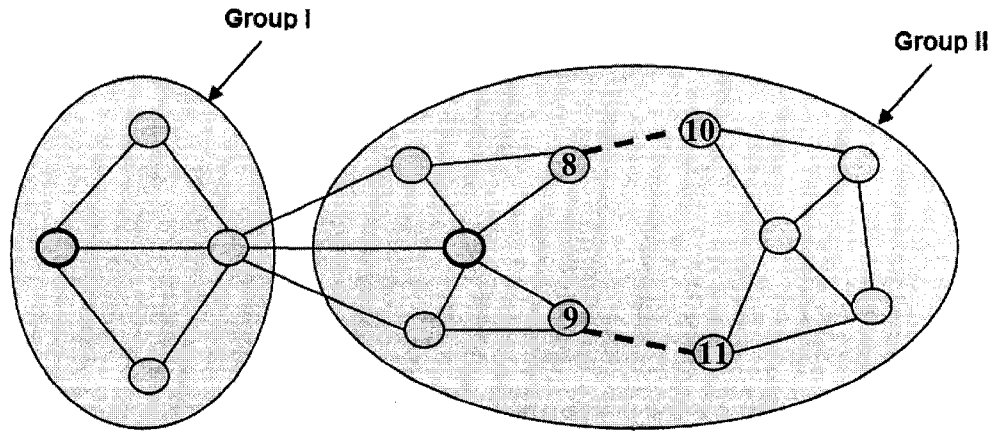


Figure 2.3 New Partitions in DCG Method
(Mahboob, 2005)

In Section 2.6.2, many different cluster schemes were reviewed. All of these schemes have their overhead and associated costs. In order to avoid the partitions within clusters and keep message overhead under control, a hybrid grouping approach was selected combining Least Cluster Change (LCC) (Chiang and Gerla, 1997) and Lowest ID Clustering (LIC) (Ephremides et al., 1987) to form the clusters because of the simplicity of operation and low cluster maintenance cost of CBRA protocol.

Comparing with other methods, CBRA makes the data replication among clusters. For example, in Figure 2.4: Firstly, the algorithm divides the whole network into clusters, and selects one node in each cluster as the cluster head; Secondly, at the relocation period, each cluster member sends its identifier and information on data item access frequencies to its cluster head; Thirdly, each cluster head calculates the sum of access frequencies of each data item; Fourthly, in the order of the access frequencies of the cluster, replicas of

the original data in other clusters are allocated to the node which has higher access frequency of the data until memory space of all nodes in the cluster becomes full; Finally, if there is free memory space left in the cluster, replicas of the original data that in this cluster are allocated in the order of access frequencies until the memory space is full (Mahboob, 2005).

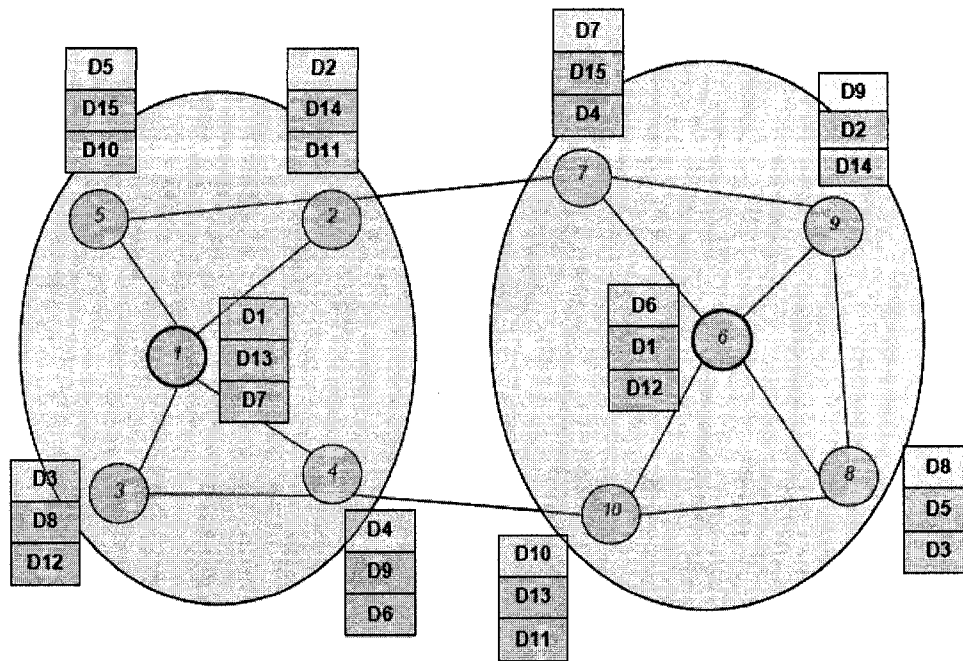


Figure 2.4 CBRA Algorithm
(Mahboob, 2005)

With this method, the network in Figure 2.3 could be divided into three clusters (Figure 2.5). All data items are replicated among these three clusters, which limited the effects of new partitioning. For example, if the new partition happens between cluster II and cluster III, the whole network will not be disturbed and the data accessibility will not decrease, because each cluster has the replication of other clusters.

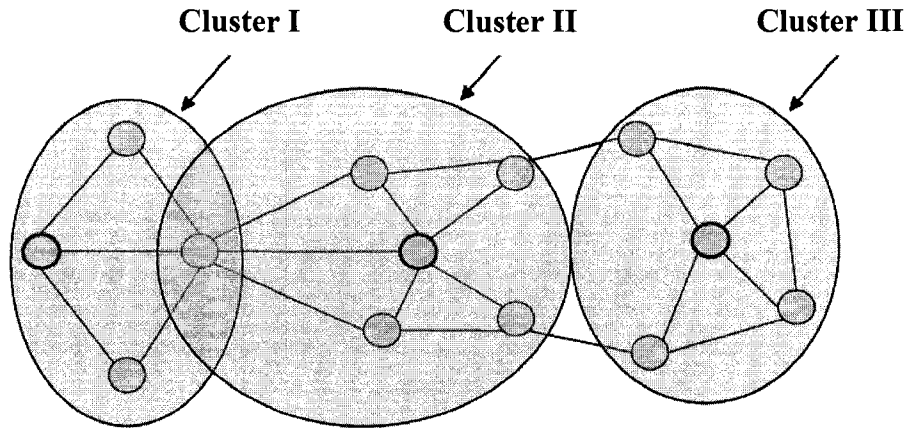


Figure 2.5 Clusters in CBRA Protocol
(Mahboob, 2005)

In CBRA, every node is associated with the cluster head, and all communication is done through cluster head. Figure 2.6 shows how a node communicates with other nodes through cluster heads. The routing protocol gives the detailed route from source node to the destination node. The route stopped at the cluster head of cluster 3, because it knows the original or replica data is in its cluster.

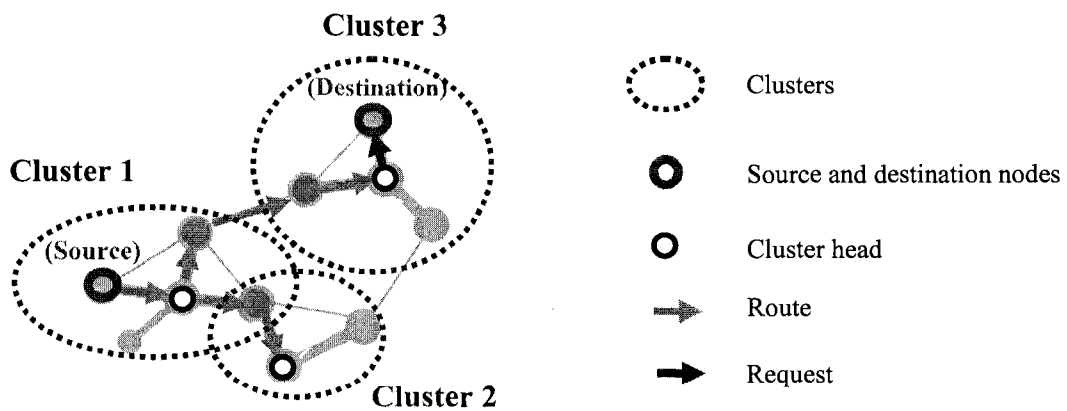


Figure 2.6 Node Communication through Cluster Heads

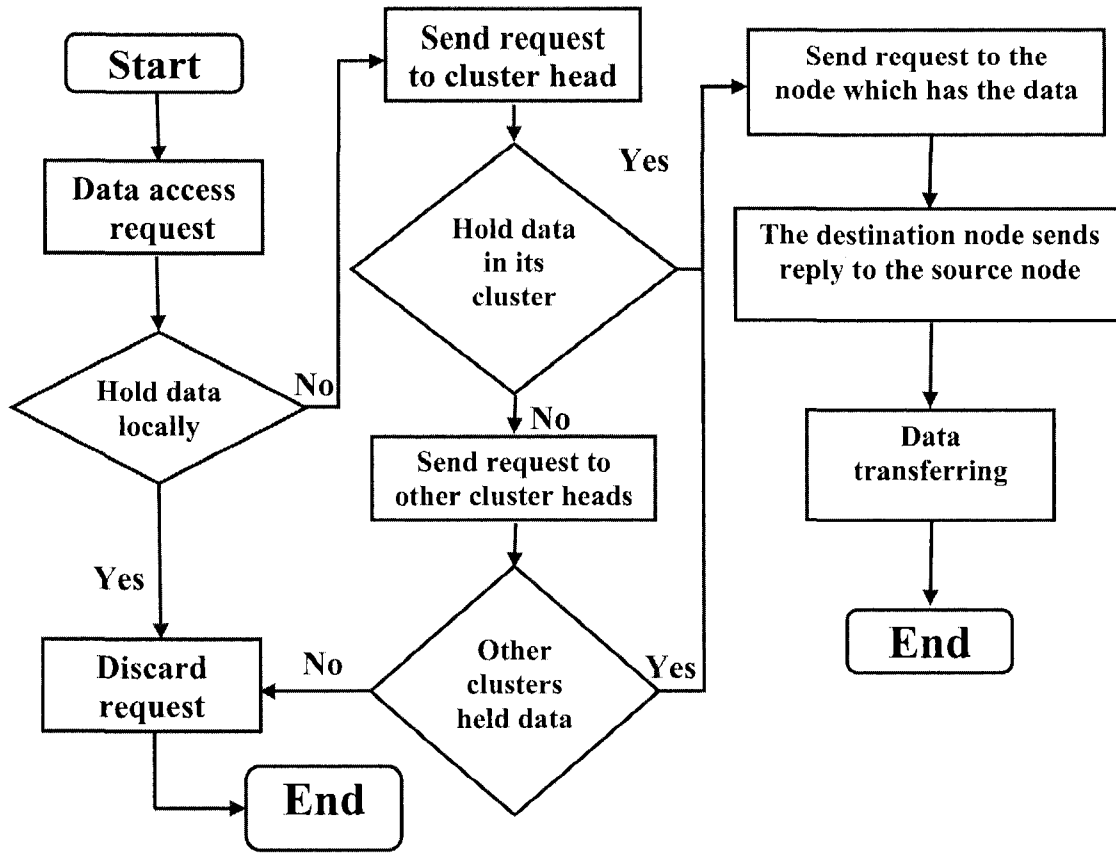


Figure 2.7 Flowchart of Data Access

Figure 2.7 explains the detailed data access algorithm: Whenever a node sends an access request for a data item, it checks if it holds the original or replica of the data. If it does, the request is successful; otherwise the request is forwarded to its cluster head. If the cluster head holds that data or replica, it will send the requested data back to the requesting node, otherwise it checks if any other node in its cluster holds the requested data. If any node does, it forwards a request to that node. Then the node will send requested data back to the requesting node. In case the cluster head could not locate the data item in its cluster, it polls the other cluster heads in the network for that data item. If any cluster holds that data, a reply will be sent back to the requesting cluster head that forwards it to the requesting node.

2.7 MOBILE AD-HOC TEST-BEDS

A test-bed is a platform on which an assortment of experimental tools and products may be deployed and allowed to interact in real-time (Buehgger et al., 2004). The following are examples of ad-hoc wireless network test-beds.

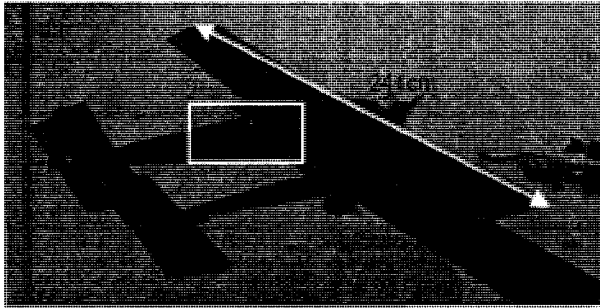
2.7.1 WIRELESS AD-HOC NETWORK TEST-BED IN DUBLIN

This test-bed covers the centre of Dublin along a 2 km route. This area is seeded with a number of custom-build wireless-enabled embedded PCs. These PCs are 3x3x6 inch containers that accommodate a stack of PC/104 boards, WiFi PCMCIA cards, and a set of antennae. The embedded PCs are hosted in apartments and shops, on traffic lights, and in phone kiosks along the route to provide a minimum level of connectivity. The test-bed can be further populated through the introduction of mobile nodes such as laptops, PDAs, and other mobile devices with wireless connectivity. This ability to be configured in various ways and to be populated with a variable number of nodes enables researchers to develop and investigate protocols and applications that are specific to the area of ad hoc networking (DSG, 2006).

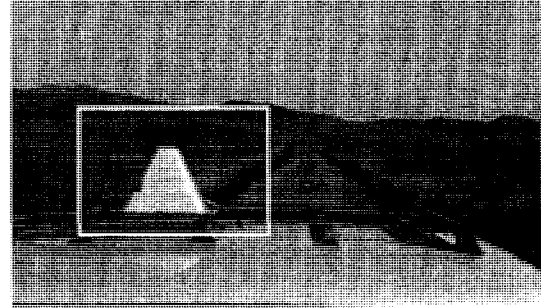
2.7.2 AD-HOC NETWORK TEST-BED AT UNIVERSITY OF COLORADO

The test-bed at the University of Colorado is designed to facilitate experiments based on wireless ad-hoc networks including radios mounted at fixed sites (Figure 2.8 (c)), on ground vehicles (Figure 2.8 (b)), and in small Unmanned Aerial Vehicles (UAVs) (Figure 2.8 (a)). Jadhav et al., (2005) built a special device named Mesh Network Radio (MNR)

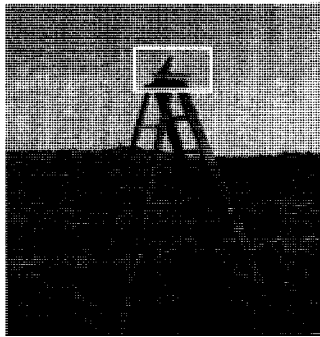
Components (Figure 2.8 (d)) inside the above positions. Furthermore, laptop computers, PDAs, and special-purpose ad-hoc radios running the Dynamic Source Routing (DSR) protocol over IEEE 802.11b serve as nodes in this test bed (Jadhav et al., 2005).



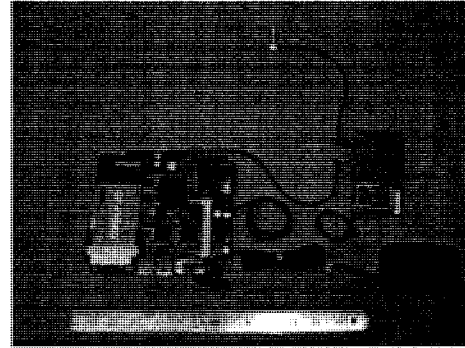
(a) Unmanned Aerial Vehicle (UAV)



(b) Ground Mobile



(c) Fixed



(d) Mesh network radio (MNR) components

Figure 2.8 Heterogeneous Ad-Hoc Radio Nodes of Colorado
(Jadhav et al., 2005)

2.7.3 WIRELESS SHUTTLE BUS PROJECT AT JOHNS HOPKINS UNIVERSITY (JHU)

This test-bed provides the JHU Security Department with the ability to track the speed and location of the escort shuttles in real-time. They used Wave Relay Mobile Router to connect the shuttle buses as an ad-hoc network. In order to locate the position of each bus, they integrate GPS receivers with the system. The scenograph of the shuttle bus system is shown in Figure 2.9. This project provides JHU students with wireless Internet access

while traveling on escort shuttles, and allows students to track current shuttle positions online to determine pickup times. It provides a completely mobile test-bed for evaluating the performance of MANET routing protocols (JHU, 2006).

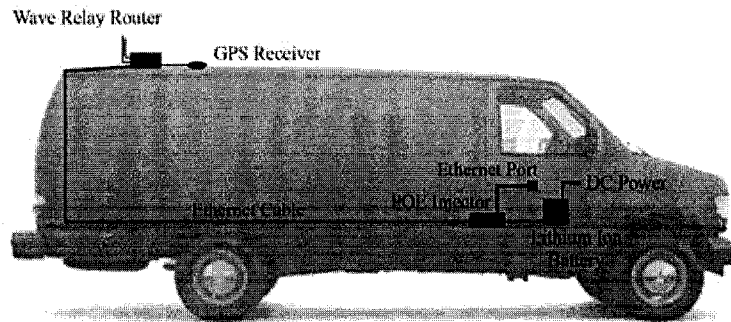


Figure 2.9 Shuttle Bus Project in JHU (JHU, 2005)

2.7.4 WIRELESS DATA COLLECTION ON CONSTRUCTION SITES

This test-bed provides a system named Wireless Network Cells (WNC) to use wireless network covering the whole site (Figure 2.10). The user on-site is equipped with a touch-screen Windows CE tablet PC, which enables the user to gain access to the server-based database over wireless network.

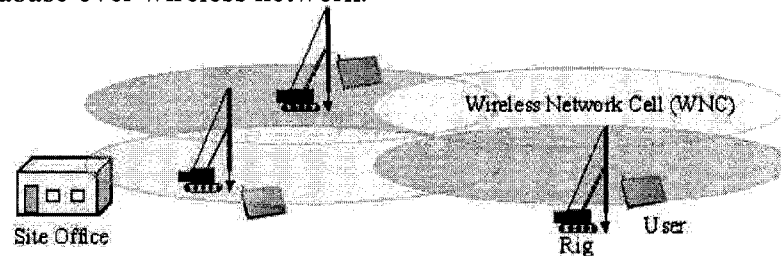


Figure 2.10 Wireless Network Cell Configuration
(Ward et al., 2005)

Each WNC provides coverage to a certain area of the site allowing roaming users to connect to the server-based database. Figures 2.11(a-d) show different types of WNC connecting with the site office (Ward et al., 2004).

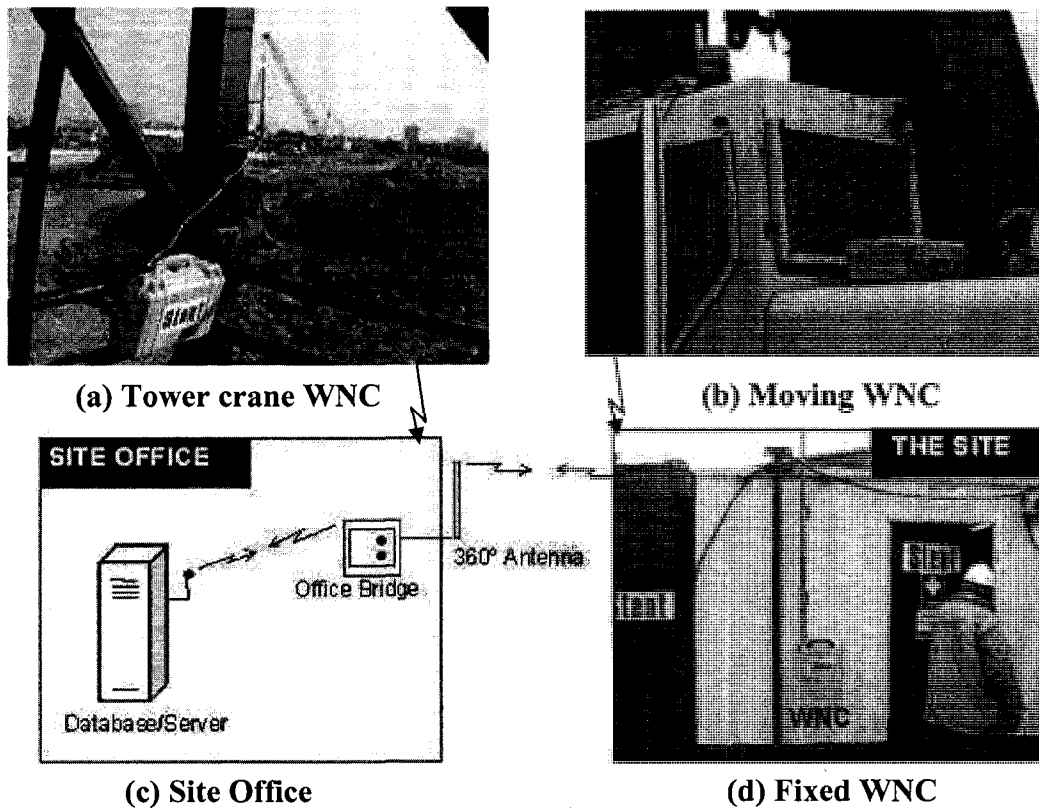


Figure 2.11 Different Wireless Network Cell (WNC)
(Ward et al., 2005)

2.7.5 MOBILE AD-HOC SPACE FOR COLLABORATION TO SUPPORT DISASTER RELIEF EFFORTS

This test-bed provides a reliable, transparent, and portable Mobile Ad-hoc Space for Collaboration (MASC) based on a short range wireless communication platform (Aldunate et al., 2006). MASC is a distributed system that provides several collaboration capabilities, highly available memory services in a transparent way, and adequate performance to distributed collaborative applications running on wearable or handheld computers. The capabilities of MASC also support the tasks of civil engineers working in disaster areas, through distributed retrieving/updating of information and the use of collaborative software tools such as CAD, GIS and structural analysis tools. The

collaborative Infrastructure Status System was implemented on MASC and was coded with Visual C++ for Windows and Windows CE. Figure 2.12 shows the system built using the services provided by MASC, which presents the stability of the infrastructure in the disaster area as assessed by the civil engineers in a first response team. Figure 2.13 shows three search and rescue exercises by using the MASC system (Aldunate et al., 2006).



Figure 2.12 Shared Views for a First Response Team in a Simulated Disaster Area
(Aldunate et al., 2006)

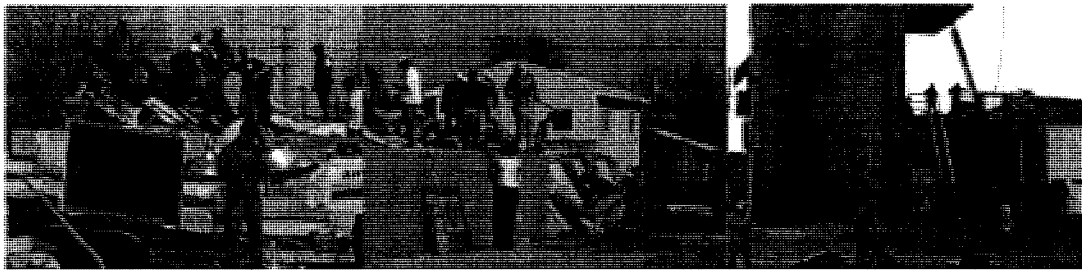


Figure 2.13 Search and Rescue Exercise Supported by MASC System
(Aldunate et al., 2006)

2.8 SUMMARY AND CONCLUSIONS

In this chapter, the literature about the available types of wireless networks, related issues, and their applications has been reviewed. Some of these wireless networks, such as

CDMA, are relatively costly and should depend on the service provider; Some wireless networks, such as DECT, have limited coverage; Some wireless networks need some type of infrastructure (e.g., signal tower, routers, etc.). If the available infrastructure is damaged because of natural or man-made disasters, all the communications on-site will stop, which will lead to extra losses and, in some cases, additional casualties. Consequently, a technique which does not need any infrastructures, and which is economical and efficient is needed. Furthermore, several research projects which considered the usage of wireless networks to support on-site communications have been reviewed. However, the research about the efficient usage of ad-hoc networking in engineering applications is still limited. On the other hand, research about new protocols aiming to improve the ad-hoc network performance is progressing using several clustering and replication techniques. However, these protocols need careful testing from the point-of-view of the engineering applications. Finally, these wireless networks have some disadvantages that may not be suitable for some special scenarios, such as construction site, emergency salvation, and military applications.

CHAPTER 3 PROPOSED APPROACH

3.1 INTRODUCTION

Efficient collaboration among team members working on site, such as inspection teams and search and rescue teams after a disaster, is important to realize the intended tasks. Real-time communication is necessary for those on-site workers to enhance their collaborative efforts. As introduced in Chapter 2, several technologies are used on site. However, these technologies have some disadvantages that may affect the work. For example, satellite telecommunications is relatively costly, DECT has limited coverage, GSM, GPRS, and CDMA depend on the service provider, and WLAN users are bounded to certain locations (Beyh and Kagioglou, 2004). Furthermore, all of the above technologies need some type of infrastructure (e.g., wiring, routers, etc.). If the available infrastructure is damaged because of natural or man-made disasters, all the communications on-site will stop, which will lead to extra losses and, in some cases, additional casualties (Yang and Hammad, 2007). Consequently, a technique which does not need any infrastructures, and which is economical and efficient is needed. Ad-hoc networking is an attractive solution for this problem because it allows on-site workers using portable devices to communicate and keep in touch with each other when they are performing their tasks (Kuladinithi et al., 2003; 2004). Minimal configuration and quick deployment make ad-hoc networks suitable for construction sites or emergency situations (Chlamtac et al., 2003).

In Chapter 3, we will investigate the following problems of deploying ad-hoc wireless networks for supporting on-site communication: (1) Defining the basic modes of

communication which are common in field applications and providing a platform for testing several wireless ad-hoc communication modes under different conditions; (2) Testing the CBRA protocol based on clustering to improve data accessibility and a simulation algorithm based on CBRA. As explained in Section 2.2.4, QoS of MANETs includes several issues, such as node mobility, route maintenance, limited battery life, etc. In this research, the main focus is on testing the QoS properties of throughput and data accessibility.

3.2 PROPOSED SYSTEM FOR TESTING AD-HOC WIRELESS COMMUNICATIONS

Efficient communication and collaboration requires that team members should be able to know about the location of each other, exchange information, communicate with each other using different communication modes, and check the performance of the network to decide what kind of communication is possible and efficient. Although most wireless protocol testing can be done with software simulations for the initial design and estimation of results, they do not realistically duplicate the physical layer. A software simulator also ignores interlayer communication, which is integral to the effectiveness of these protocols. This makes hardware testing critical (Sanghani, 2003). Therefore, in order to test several on-site communication modes using mobile devices (e.g., laptops), we developed a prototype system called *Ad-hoc Messenger* which allows users to communicate with each other by using an ad-hoc wireless network. This system (Figure 3.1) is based on IEEE 802.11 standards, and it supports TCP/IP (IP v4 and v6). It uses

AODV as the routing protocol, which is implemented in the function JAdhoc (ComNets, 2006). This system runs on Windows XP platform in Java environment. There are six modules in this system: position messaging, text messaging, video and voice communication, file transferring, network throughput testing, and JAdhoc.

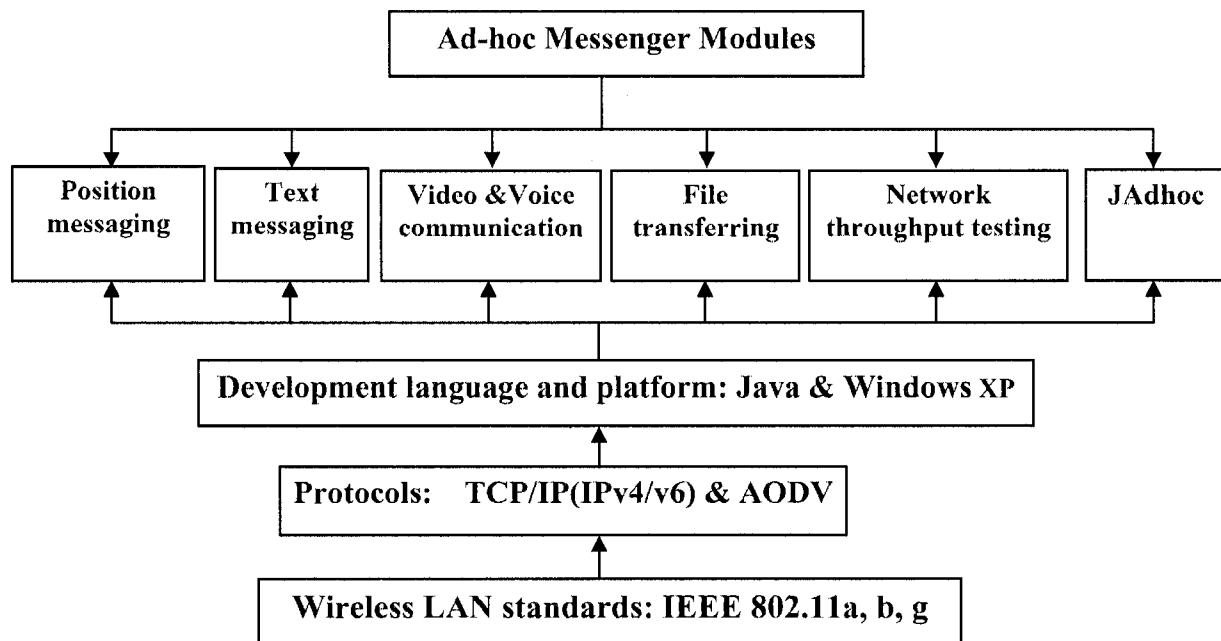


Figure 3.1 System Design of *Ad-hoc Messenger*

3.2.1 DESIGN LOGIC

The design of the prototype system is based on the seven-layer structure of Open Systems Interconnection as shown in Figure 3.2. Firstly, the IEEE 802.11 standards will work based on the physical layer and data link layer. We can use different types of network adapters or modify the parameters in the advanced properties of each wireless network adapter in order to control this layer. Secondly, the AODV routing protocol is running in the network layer to give the route for each pair of source and destination nodes, or we can use a bridge to connect several nodes together and give the route manually. Thirdly,

in the application layer, in order to check our approach, we developed our proposed system “*Ad-hoc Messenger*”, which includes many communication methods that can be used on site.

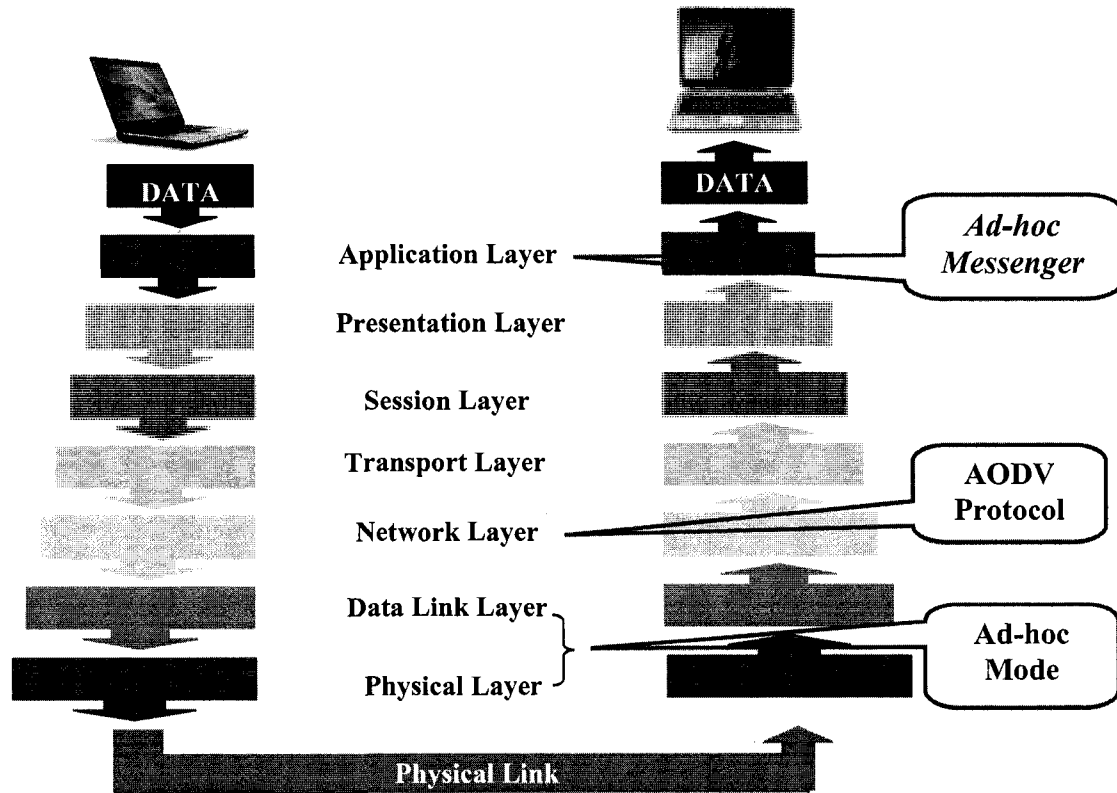


Figure 3.2 Seven Layers of Open Systems Interconnection (OSI)

3.2.2 NETWORK ROUTING

Ad-hoc mobile wireless networks present several technical challenges, one of which is routing. For wireless settings, the Internet routing protocols are not applicable (Toh et al., 2004). As discussed in Section 2.3, many routing protocols have been developed for ad-hoc networks, and the AODV routing protocol is considered suitable for ad-hoc wireless networks with many clusters (Lee et al., 2003). In our prototype system, we used the AODV as the routing protocol. The AODV algorithm enables dynamic, self-starting, multi-hop routing between participating mobile nodes to establish and maintain an ad-hoc

network. It allows mobile nodes to obtain routes quickly for new destinations, and does not require nodes to maintain routes to destinations that are not in active communication. In addition, it allows mobile nodes to respond to link breakages and changes in network topology in a timely manner (Charles et al., 2003).

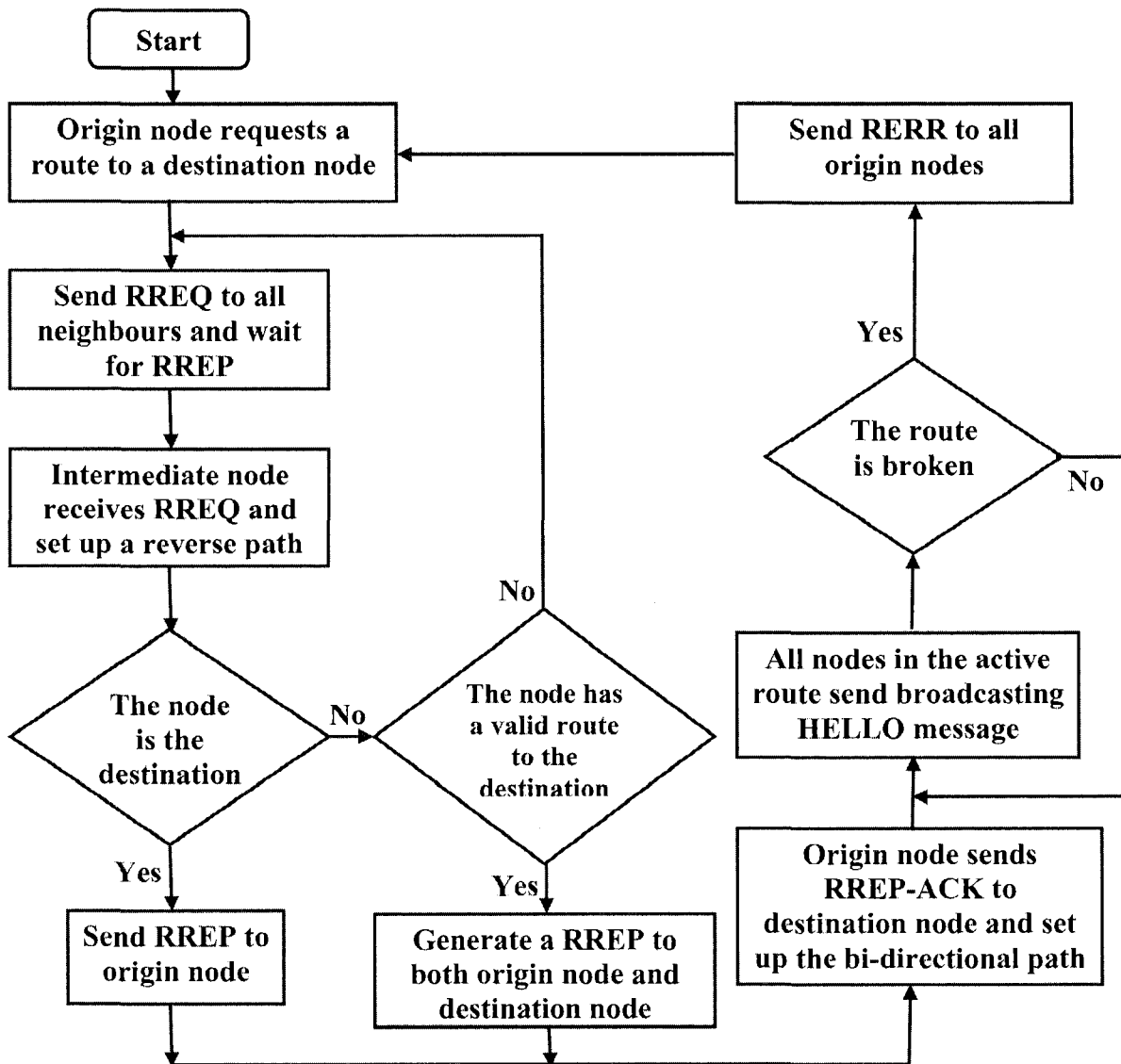


Figure 3.3 Algorithm of JAdhoc Function
(Adapted from ComNets, 2006)

In our system – Ad-hoc Messenger, we combined a function named JAdhoc into our system. JAdhoc is a function developed at Bremen University in Germany (ComNets, 2006) as an implementation of the AODV routing protocol. In our system, this function works on the network layer. When a node generates the access request, JAdhoc gives the detailed route from the source node to the destination node in the ad-hoc network. The basic algorithm of JAdhoc is explained in the following paragraph (Figure 3.3).

When a node needs a route to a destination node, it initiates a route discovery process. The route manager class involves a network wide flood of RREQ targeting the destination node and waiting for a RREP. If an intermediate node receives the RREQ, it first sets up a reverse path to the origin node using the previous hop of the RREQ as the next node hop on the reverse path. If the intermediate node has a valid route to the destination node, it will generate a RREP to the origin node and a gratuitous RREP to the destination node; else the RREQ is rebroadcast. Meanwhile, the duplicate copies of RREQ received at any node are discarded (duplicate copies are identified by RREQ ID maintained for the origin node).

When the destination receives a RREQ, it also generates a RREP. The RREP is routed back to the origin node via the reverse path. As the RREP proceeds towards the origin node, a forward path to the destination is established. The origin node can send RREP-ACK to the destination upon receiving the RREP in order to assure the reliability of the bi-directional path. At the same time, each node, which has active routes, starts multicasting a special RREP message with a Time To Live (TTL) field set to 1. This is

called a HELLO message. The link layer connectivity to the immediate neighbors can be detected using the link layer information or listening to HELLO messages. When a node detects the link failure, a route error (RERR) is sent back via separately maintained precursor lists to all origin nodes that are affected by the failed link. When the origin node receives the RERR, it can start a route discovery process again. During the process, unused routes in the routing table are expired using a timer-based technique (ComNets, 2006).

3.2.3 COMMUNICATION FUNCTIONS IN AD-HOC MESSENGER

The following information are wirelessly transmitted in *Ad-hoc Messenger* (Figure 3.1):

(1) The locations of team members within a 2D or 3D model of the site are tracked using Global Positioning System (GPS) receivers or other tracking methods and communicated to other members of the team; (2) The team members can exchange information in different formats (text messages, voice, and video); (3) In order to share files, the users can transmit files to each other; and (4) A user can test the throughput of the network, and then decide which communication method he/she should use. This testing is important because users may not know how far their colleagues are or if they can receive a large file or communicate with text, voice, or video. Our system has a function to test the throughput of the network between two devices using the average data transmission speed of the current connection. Then, based on the measured throughput, the system suggests a suitable combination of communication modes (text, voice, and video). The text messaging function is a local area broadcasting system. Text messaging is preferable when the distance between clients is long or their mobile devices do not have enough

battery. In other cases, the users can select video and/or voice communications depending on the conditions (battery life, distance, etc.). In case a client disconnected from the network because of mobility, the system will continuously check for other nodes and re-establish the connection if a node became within range.

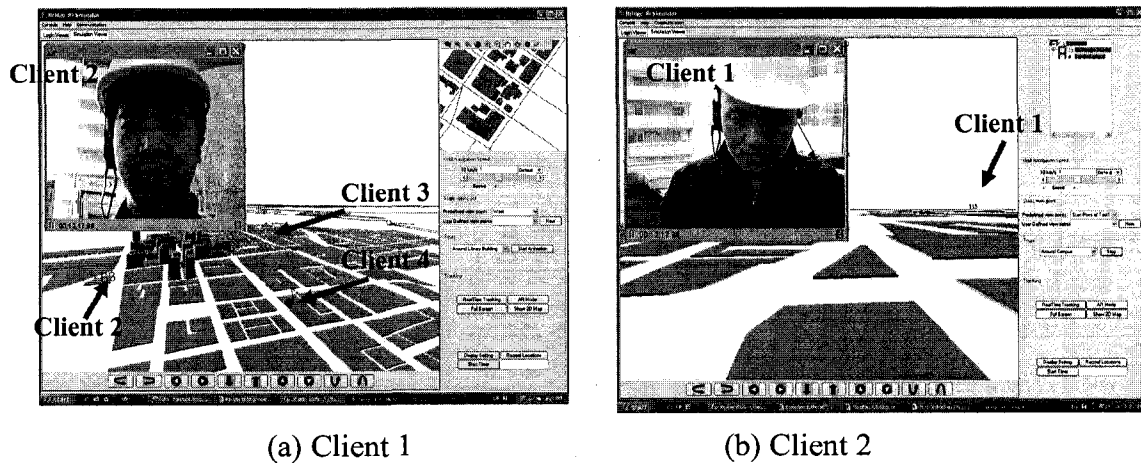
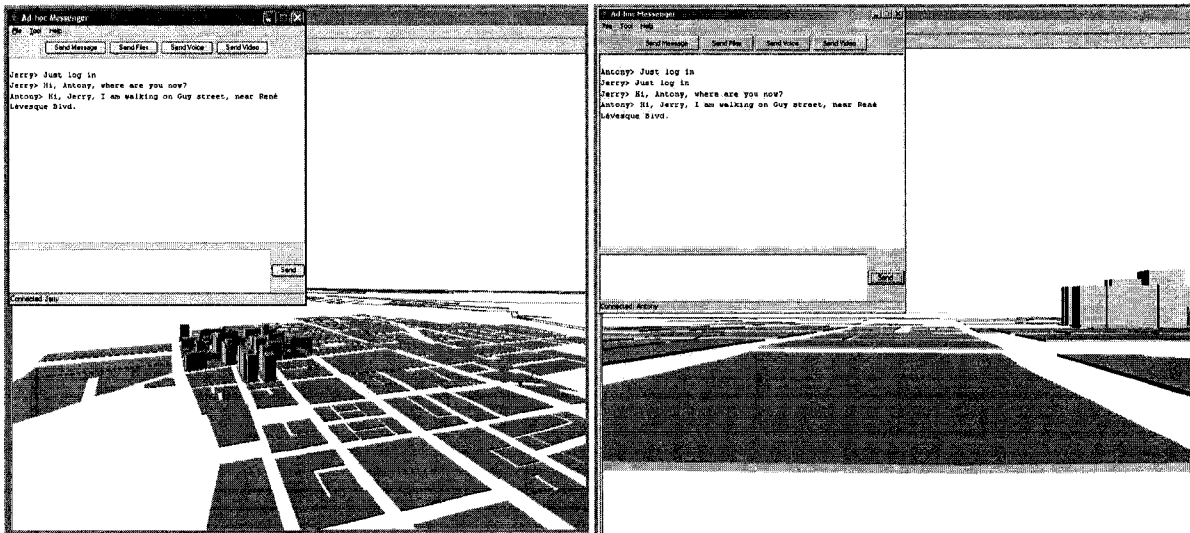


Figure 3.4 Communication between Two Clients in *Ad-hoc Messenger*

(1) Position Messaging

In some situations, it is difficult for a member of a team to find the locations of his/her colleagues. For example, in a search and rescue team, workers move separately in different directions. If they want to cooperate, they should know about the location of their colleagues and the target position, and find the best way to go there. Our system is linked with 2D and 3D maps (Mozaffari, 2005), and it sends the local position to other clients. Thus people who are in the same group could find the location of each other, and also can go to their target locations through the shortest path. Figure 3.4 shows an example of position messaging in *Ad-hoc Messenger*. From the figure, we can see the locations of clients moving around the campus of Concordia University. Client 1 is

playing the role of the team leader, so he/she can see all clients from a high point of view. This function is very useful in emergency situations, such as the shooting accident at Dawson College, Montreal, September 2006. If the police officers have had a system with similar functionalities, they might have easily found the cafeteria inside Dawson College where the crime happened, and less people would have been hurt.



(a) Client 1

(b) Client 2

Figure 3.5 Text Messaging in *Ad-hoc Messenger*

(2) Text Messaging

The text messaging function of the system is a local area broadcasting system, which means members of the same group can see the message on the messaging panel. Text messaging is preferable over voice or video modes of communication when the distance between clients is very long or their mobile devices do not have enough battery. Figure 3.5 shows an example of two clients using text messaging.

(3) Video and Voice Communication

In construction sites, emergency scenes, or battlefields, people need to talk with each other and sometimes they need video communication. The users can select the suitable mode of communication depending on the situation: video with voice, or only voice communication. If the devices have enough battery, and the clients are within a suitable communication distance, the system can support a good communication quality of service. Figure 3.4 shows an example of two clients using video and voice communication.

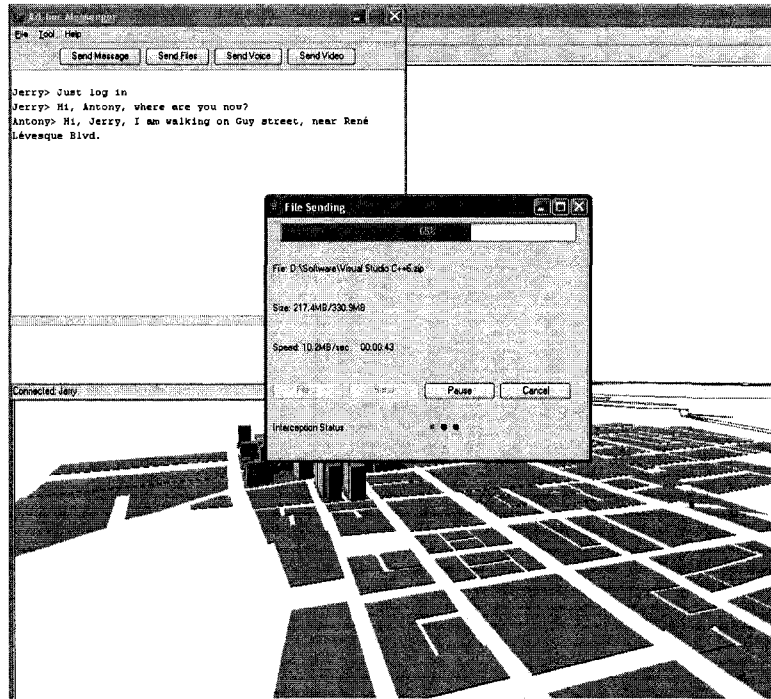


Figure 3.6 File Transferring in *Ad-hoc Messenger*

(4) File Transferring

Sharing files is an important function in field operations. Team members need to send reports to the team leader, receive commands from the leader, or send images or video

clips to each other. Our system can support any file formats, from a small text file, to a large video file of several gigabytes. Figure 3.6 shows an example of sending a file to another client. The user can see the size of the file, the percentage of the transmitted part, and lapsed time. If the connection is cut due to any reason, the user can restart the transmission, and the system can find where the file was stopped, and continue to transmit the file from that point.

(5) Network Throughput Testing

In real situations, people do not know how far are their colleagues from them when they want to communicate with each other, so they could not know if they can send a very big file or communicate with video. We suggest that the users select the communication methods shown in Table 3.1 based on the measured throughput as will be discussed in Chapter 4. Our system has a function to test the throughput of the current network between two clients.

Table 3.1 Communication Methods vs. Throughput Range

| Throughput (kbps) | Recommended communication method |
|--------------------------|---|
| < 50 | Text only |
| 50-100 | Text and voice |
| > 100 | Text, voice and video (Minimum resolution: 128 × 96 pixels, 15 fps) |

3.2.4 PROPOSED TESTS

In order to test our proposed approach, we considered two different types of tests based on the routing types: manual routing using a bridge, and AODV routing.

3.2.4.1 TEST WITH A BRIDGE

The first test is using a bridge as the connection node between the source and destination nodes. In this test, the bridge node should be a powerful portable device that has at least two wireless network adapters. Furthermore, the communication route is already set up manually by combining these two wireless adapters together as one bridge. Figure 3.7 shows how nodes communicate with each other through the bridge node. In this case, the roles of the bridge and other nodes could not be exchanged, and all communication between two domains is done through the bridge node (The detailed configuration is explained in Appendix B).

Using a bridge has some disadvantages: (1) The intermediate node (the bridge) should be configured in a specific way with two IP addresses, and if it is shut down, the whole network will crash; and (2) The combination of two wireless adapters is difficult because of the incompatibility of different types.

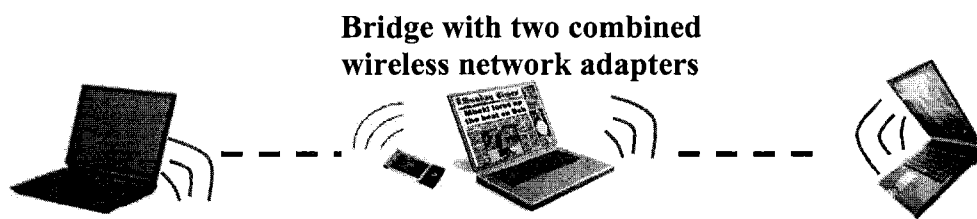


Figure 3.7 Communications through a Bridge

3.2.4.2 TEST WITH AODV ROUTING PROTOCOL

The second test is using AODV routing protocol to solve the routing problems. In this test, the nodes are self-organized, and the only requirement for the mobile nodes is to

have a communication system with its routing protocol. Therefore, any device in this test could become the intermediate node, and the route will be found by the routing protocol. Figure 3.8 shows how nodes communicate through the intermediate nodes with AODV routing protocol. Because every node uses AODV routing protocol, any of them could become the intermediate node (The detailed configuration is explained in Appendix B).

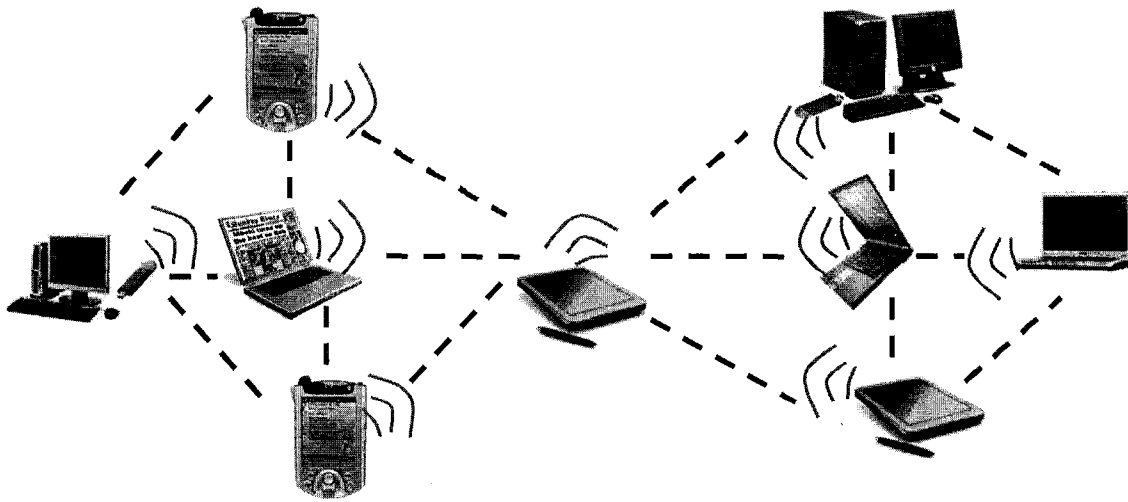


Figure 3.8 Communication with AODV Routing Protocol

3.3 AD-HOC CLUSTERING SIMULATION

Because of the instability of ad-hoc networks, many issues could affect data accessibility, such as area size, number of nodes, speed of nodes, and communication range of the network adapters. Simulation is used to analyze different effects of data accessibility in large applications of ad-hoc networks. Furthermore, simulation is used in stead of testing because of the limitation of wireless devices, space, weather, and environment.

As explained in Section 2.6, the CBRA protocol assumes an ad-hoc network where each mobile host generates access requests for data items held by other hosts in the network as

originals. The network protocol employs cluster-based routing and replication. Each host in the network is associated with a cluster head, and inter-cluster communication goes through cluster heads. Each host informs its cluster head when it generates a data item. The access requests to a data item are successful in the following cases: (1) the mobile host generating the request holds original/replica of the data item, or (2) any host within the cluster holds the original/replica of the data item, or (3) any host in other clusters holds original/replica for the data item.

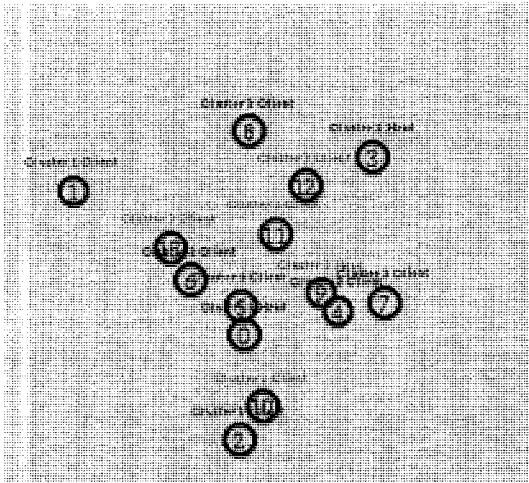
Table 3.2 Simulation Parameters

| Parameter | Range | Default value |
|--|--------------------------------|------------------------|
| Number of nodes | 14-50 nodes | 14 nodes |
| Number of clusters | 3-10 clusters | 3 |
| Number of nodes in each cluster | 4-5 nodes | 4, 5, 5 |
| Area size | 50×50 - 600×600 m ² | 300×300 m ² |
| Wireless range | 50-300 m | 100 m |
| Moving speed | 1-30 m/sec. | 2 m/sec. |
| Simulation time | 500 sec. | |
| Pause time | 2 sec. | |
| Number of original data items per node | 3 | |
| Data size | 1 kb | |
| Memory size per node | 10kb | |
| Replica allocation period | 100 sec. | |

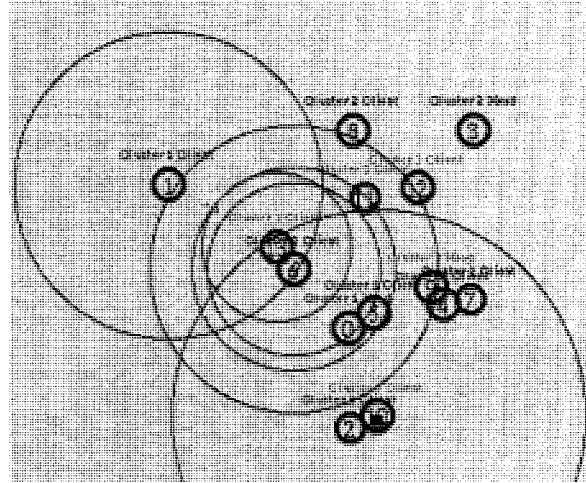
In the simulation, we focused on how to implement CBRA protocol in Ns2 to compare different scenarios and to improve data accessibility in MANETs. The ad-hoc network model uses the following assumptions: (a) All nodes are assigned to clusters with a maximum of 5 nodes per cluster; (b) The access frequency of each node is fixed; (c) All the communications are done through the cluster heads; (d) The mobile clients are distributed and move randomly in the testing area. Table 3.2 summarizes the parameters of our simulation and their value ranges used to study the effects on data accessibility. Data accessibility is defined as the ratio of number of successful requests to the total

number of requests during simulation time. When testing the effect of one parameter, we gave the other parameters the default values shown in the table. We used data accessibility to compare different results.

The simulation code includes the main program *.tcl file, routing protocol aodv.cc, and other related programs. In order to get different results, we used the Ns2 commands to generate different scenarios, and modified the code to get various values of the parameters, such as the number of nodes, area size, moving speed, etc. The detailed operation is explained in Appendix C.



(a) Nodes are moving in the area



(b) Nodes are sending broadcast

Figure 3.9 Simulation Animation

At the end of each simulation, several data files were generated, such as the *trace* file, which contains all the data transmission information during the simulation, and the *nam* file, which contains all the position and action information of each node during the simulation. We developed a program in AWK language to extract some useful data from the trace file, such as delivery ratio, delay time, throughput, etc. In order to visualize the

simulation results, we use a special Ns2 tool, the Network Animator *nam* to display an animation of the simulation (Figure 3.9).

3.4 SUMMARY AND CONCLUSIONS

In the first part of Chapter 3, we presented a new approach to investigate problems related to deploying ad-hoc wireless networks for supporting on-site communication and collaboration. Several modes of communication which are common in field applications have been considered including location information, text messaging, voice and video communications, and file transmission. In addition, in order to verify our proposed approach, two types of testing are considered by using different routing methods: bridge (manual routing), and self-organized routing (AODV routing). This approach will be implemented in Chapter 4. Furthermore, the proposed two test scenarios will be tested in the real case studies. In the second part of Chapter 3, a simulation model based on CBRA was used to test data accessibility. This approach will be implemented in Chapter 4 to analyze which situation could be best for the application of ad-hoc networks.

CHAPTER 4 IMPLEMENTATION AND TESTING

4.1 INTRODUCTION

In the first part of this chapter, a prototype system is developed following the framework architecture of the *Ad-hoc Messenger* introduced in Chapter 3. Then, two tests in Concordia downtown campus are used to demonstrate the prototype system. In the second part, based on CBRA protocol introduced in Chapter 2, a real-time clustering simulation is implemented and the results are used to study the effects of data accessibility.

4.2 SELECTION OF DEVELOPMENT TOOLS

Java is a network-oriented programming language invented by Sun Microsystems specifically for writing programs that can be safely downloaded through the Internet and immediately run without fear of viruses or other harms. The reason that we selected Java as the development platform for our prototype system is that it is more stable than the other program languages and it could be used on several operating systems, such as Windows XP, Linux, Mac, etc. Java programs can be installed on most devices, such as laptops, PDAs, and mobile cell phones.

We selected JBuilder (2005 or 2006) from Borland as the development tool for Java. Furthermore, we combined and modified part of the open source code of the JAdhoc function from Bremen University to implement the AODV routing protocol. Detailed instructions about the software requirements and installation are given in Appendix A.

We used Ns2 (USC, 2005) software to simulate the different scenarios of ad-hoc clusters with CBRA protocol and to test the data accessibility for a group of mobile clients to desired data. Using this simulation tool, it is possible to simulate new protocols that are not easy to test in the real world because of the hardware limitation or other difficulties in realizing the test. Ns2 runs in the Linux environment. Detailed instructions for the installation and configuration of Ns2 are given in Appendix C.

4.3 IMPLEMENTATION OF THE PRTOTYPE SYSTEM

4.3.1 USER INTERFACE DEVELOPMENT

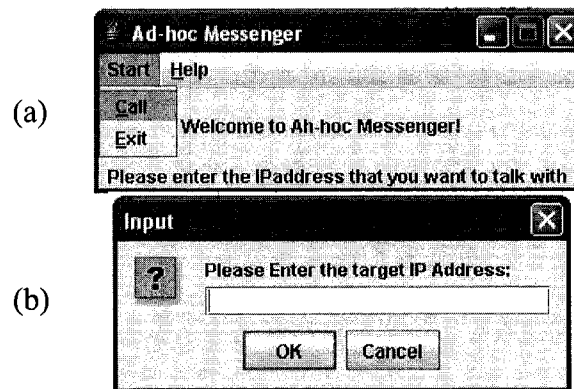


Figure 4.1 Start Window of *Ad-hoc Messenger*

Before starting the system, the user should configure the routing protocol as explained in Appendix B. When the user starts the *Ad-hoc Messenger* system, the system will display the start window (Figure 4.1) and JAdhoc control window (Figure 4.2). Then the user should follow the following steps: (1) Click the “*Start*” button in the JAdhoc control window (Figure 4.2) to activate the routing protocol; (2) Click the button “*Start*” in the

start window (Figure 4.1 (a)), and click the “*Call*” button in the menu item (Figure 4.1 (b)) to input the IP address of the server.

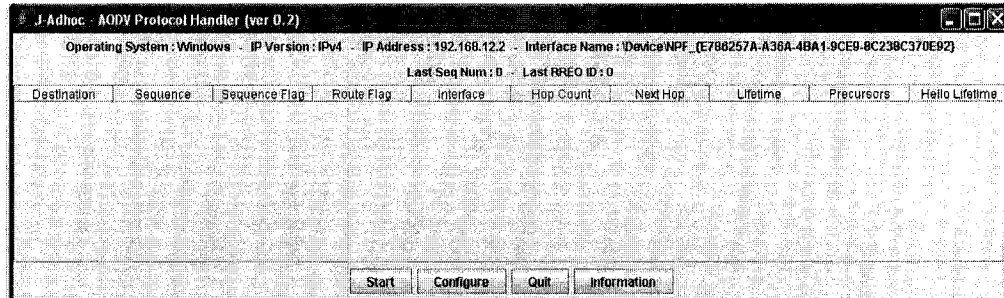


Figure 4.2 JAdhoc Control Window

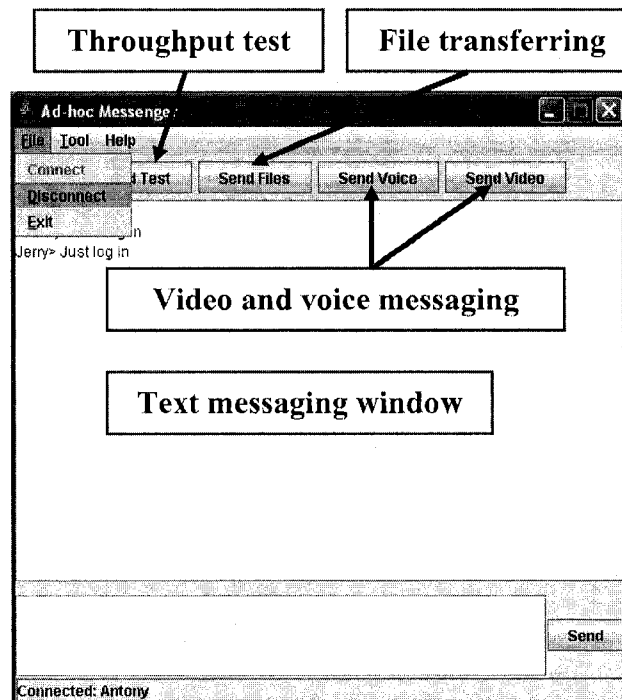


Figure 4.3 Main Control Panel of Ad-hoc Messenger

After all users login to the system, every client can see their names on the text messaging window (Figure 4.3). First of all, they should use the throughput test function to test the quality of the current network, and then select the suitable communication method based

on the system's suggestion. When they finish the communication, they can either click “disconnect” button to log off the system, or they can just close the window.

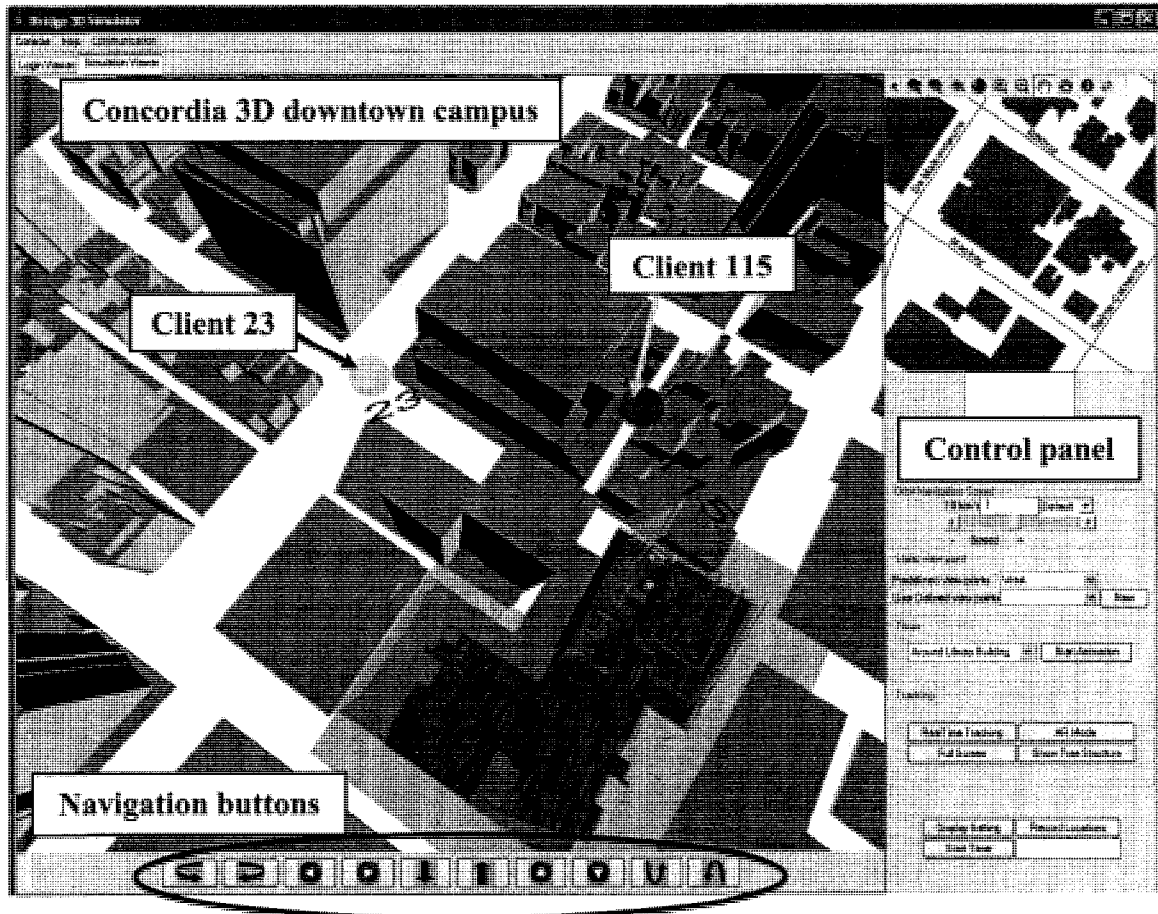


Figure 4.4 Position Messaging Control Window

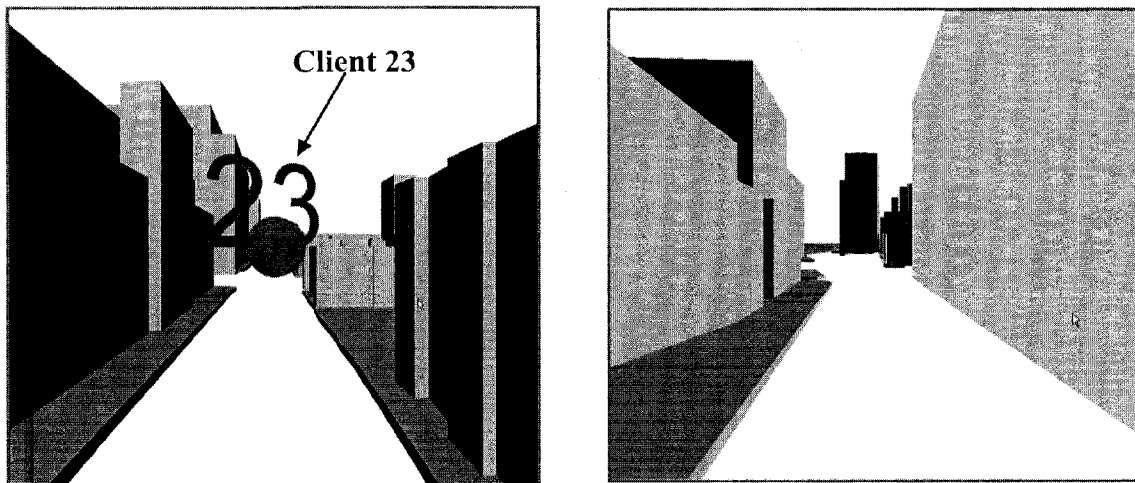
The function of position messaging is in a different system (Mozaffari, 2006), which has a 3D navigation function. Figure 4.4 shows the main control window of the position messaging from the point of view of the server (representing the location of the team leader). In the 3D map, the current locations of all clients are shown and broadcast locations to other clients. In mobile applications, the locations are found based on GPS or other tracking methods. In addition, the system can be used in virtual reality (VR) mode

for indoor applications, such as training of field workers before they go to the field. Navigation buttons and the control panel can be used to navigate in the 3D model and the location of the view platform is used to represent the current location of each user.

4.3.2 FUNCTIONS OF THE PROTOTYPE SYSTEM

(1) Position Messaging

The position messaging is server-client based system, which uses Java socket to transfer data from the clients to the server. Java threads class is used to collect all information from different clients. Furthermore, the server uses broadcasting to send location information to all clients.



(a) Screenshot from Client 115

(b) Screenshot from Client 23

Figure 4.5 Client to Client Monitor

In order to visualize the movement of each client, we use balls to represent clients with different colors and use their IP addresses as their names. In the system, each client can see the movement of other clients on the screen using first person view (Figure 4.5). The

server representing the team leader can monitor all clients and see their movements (Figure 4.4).

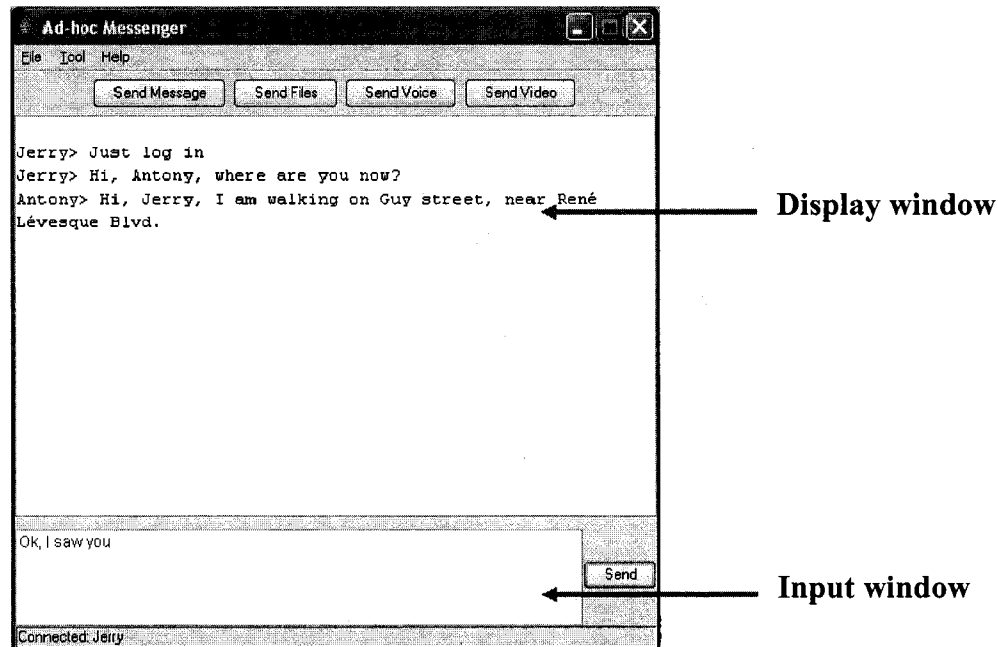


Figure 4.6 Text Messaging

(2) Text messaging

The text messaging function is a broadcasting system. Each client types its message in the input window. After clicking on the send button, all information, including the name and IP address of the client, will be sent to the server. Then, the server uses MULTICAST_ADDRESS to broadcast this message to all clients. Finally, all clients can see the message in the display window (Figure 4.6).

(3) Video and Voice communication

In the video and voice communication, we mainly used two Java classes: Real-time Transport Protocol (RTP) and Java Media Framework API (JMF). RTP has become a widely implemented Internet-standard protocol for transport of real-time data, including

audio and video. It can be used for media-on-demand as well as interactive services such as Internet telephony. RTP consists of a data and a control parts (RTP, 2006).

The JMF enables audio, video and other time-based media to be added to applications and applets built on Java technology. This optional package, which can capture, playback, stream, and transcode multiple media formats, extends the Java 2 Platform, Standard Edition (J2SE) for multimedia developers, by providing a powerful toolkit to develop scalable, cross-platform technology (JMF, 2006).

The video and voice communication function is a server-client based system. We used JMF to capture the video through a digital camera, and then to display the video on the monitors of other clients. We used RTP to transfer the video stream between clients (Figure 3.4).

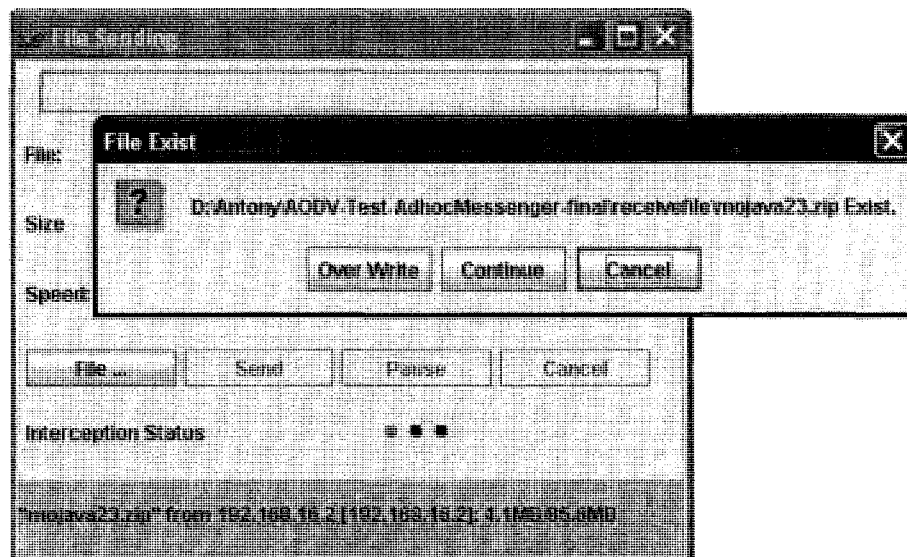


Figure 4.7 Break Point Continue Transmission

(4) File transferring

In this function, we mainly used a *DataInputStream* and *DataOutputStream* to transfer files. A data input stream lets an application read primitive Java data types from an underlying input stream in a machine-independent way. An application uses a data output stream to write data that can later be read by a data input stream. A data output stream lets an application write primitive Java data types to an output stream in a portable way. An application can then use a data input stream to read the data back in (Java.io, 2006).

Because of the instability of ad-hoc networks, file transferring could be interrupted by a disconnection of the network. That leads to uncompleted file transmission. In order to solve this problem, our system has a function named *break point continue transmission*. When a client asks another client to send a file, the system will check if a file with the same name exists in the saving folder of the client. If it does, the system will give three options to the client: continue transmission, overwrite, or cancel (Figure 4.7). If the client selects continue, the system will check the break point for the file, and continue to transfer the file from that point in the last transmission.

(5) Network throughput testing

This function is based on the file transferring function. As discussed in Section 3.2.4, the system will give the recommended communication method to the clients. Then the clients will use this method to communicate with each other. After clicking the testing button, the system will send several default files to the other terminal, from 100 KB file to 20 MB file. During the transmission, the system will do some calculation, if the transmission time of the current file is less than 5 seconds, it will send a bigger testing file; if not, it

will stop the transmission. At the end of the test, the system will display the average throughput of the current connection. Then the user can select the proper mode (text, voice, or video) and whether he/she can send large files. Figure 4.8 shows an example of throughput testing. Based on the current throughput, 10.8 MB/sec, the system suggests to the user to use video communication (Using Table 3.1).

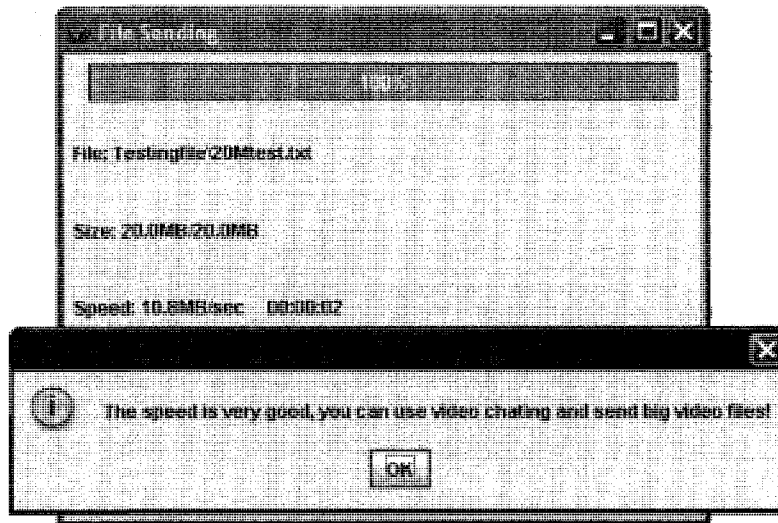


Figure 4.8 Throughput Testing in Ad-hoc Messenger

(6) JAdhoc

The original code was developed by Bremen University (ComNets, 2006), and was modified and combined with our system.

4.4 TESTING THE AD-HOC MESSENGER

As explained in Section 2.2.4, QoS of MANETs includes several issues, such as node mobility, route maintenance, limited battery life, etc. In this testing, the main focus is on testing the QoS properties of throughput. The purpose of testing the *Ad-hoc Messenger* is to measure the communication throughput of file transfer function under different

methods of routing (bridge or AODV routing protocol), the effects of distance, and the noise caused by barriers and people. Some factors of wireless devices could be modified according to the requirements (e.g. the communication range of the wireless adapters could be adjusted by changing the power of the wireless adapter in the advanced configuration of wireless adapters). In the testing, we assume that all wireless devices have full power and do not move when they are communicating with others. We did the indoor testing in the fourth floor of the CB Building and the ninth floor of the EV Building (bridge and AODV routing) in Concordia University Sir George Williams Campus, and we did the outdoor testing on Rene Levesque Street. Figure 4.9 shows the testing locations in the fourth floor of the CB Building. Figure 4.10 gives an example of wireless nodes distributed in the ninth floor of the EV Building.

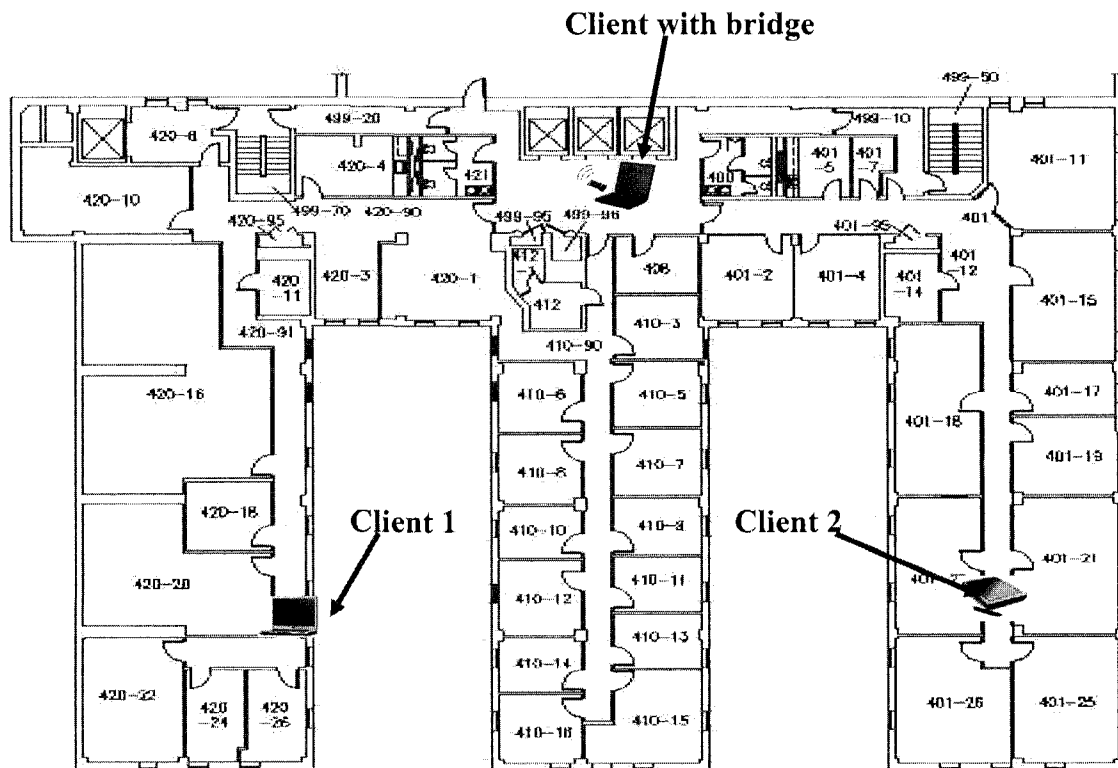


Figure 4.9 Testing Locations in the Fourth Floor of CB Building

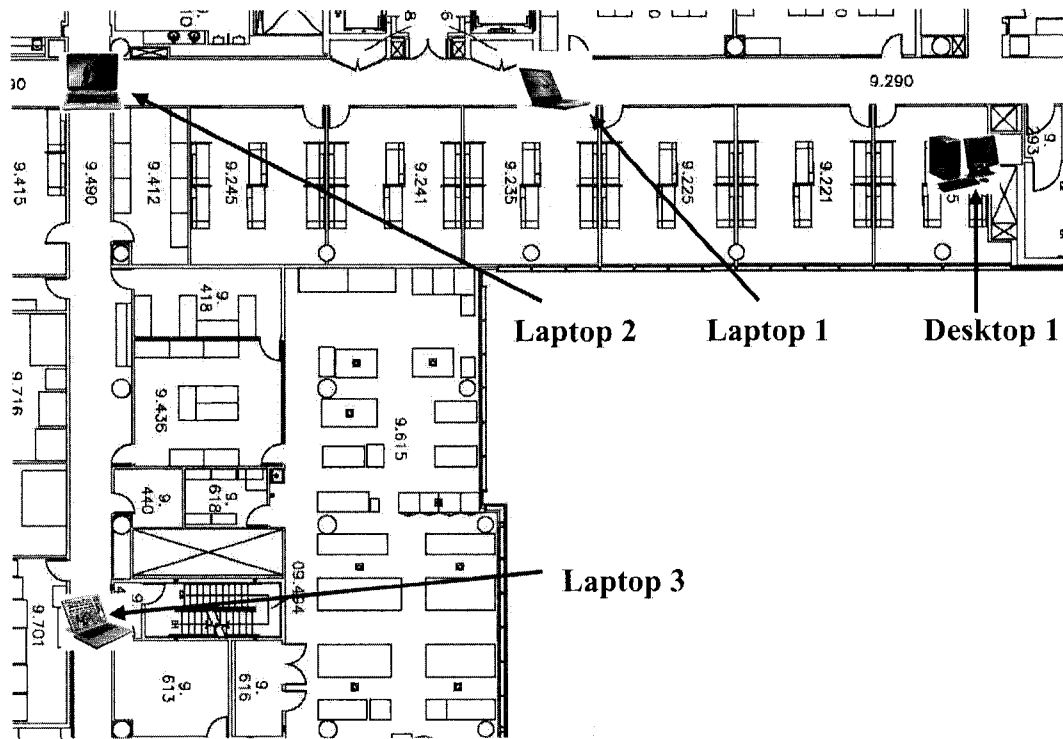


Figure 4.10 Example of Distribution of Wireless nodes

Figure 4.11 shows an example of the devices used in the testing. In this figure, the field worker is equipped with a digital camera, ear phone, and microphone. All these devices are connected to the portable tablet PC.

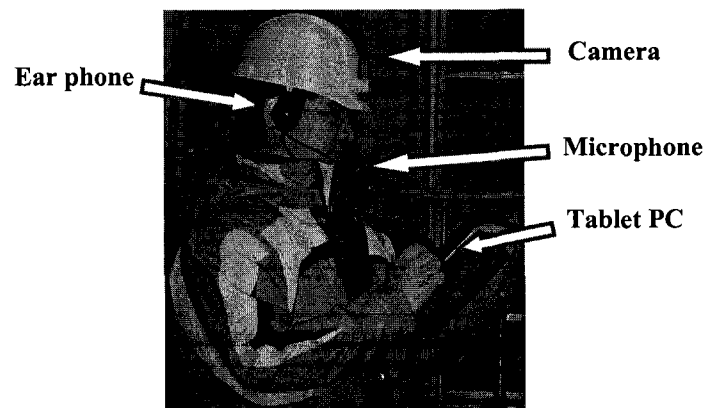


Figure 4.11 Devices Used in the Prototype System Testing

4.4.1 INITIAL TESTING

In this test, the first step is to measure the working range of a single wireless adapter. We used Toshiba Tecra M4 with internal wireless adapter (g type) to send an audio file to another laptop (Toshiba Satellite M30 with internal wireless adapter (g type)). We recorded the connection status and listened to the quality of the audio. We did these tests inside the CB Building and along the Rene Levesque Street. Finally we got the indoor and outdoor ideal connection speeds of the wireless adapter (g type) as shown in Figure 4.12. This figure shows that the ideal connection speed decreased sharply in the case of indoor test and the connection was lost at the distance of 125 m because of the internal walls inside the building. In the case of the outdoor test, the ideal connection speed decreased slowly and the connection was lost at the distance of 600m.

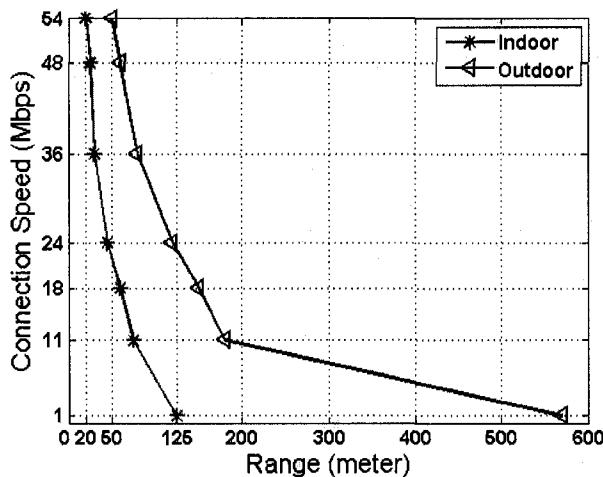


Figure 4.12 Connection Speed of Wireless Adapter (g type)

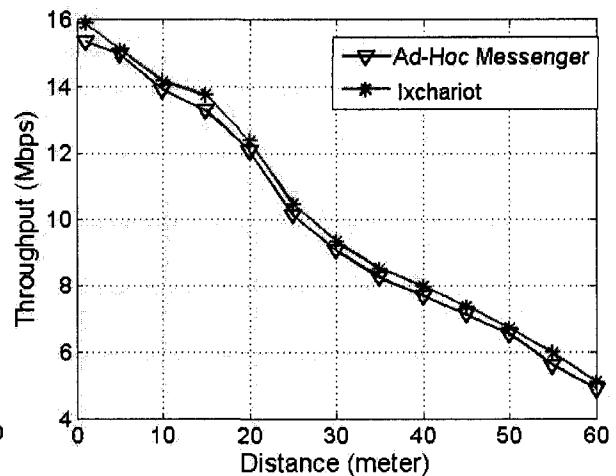


Figure 4.13 Indoor Testing with Wireless Adapter (g type)

Figure 4.13 shows the results of throughput of our indoor testing with wireless adapter (g type) based on the *Ad-hoc Messenger* and a testing tool for comparison, Ixchariot (Ixia, 2006). We also tested the video and voice communication. Because there were many

walls in CB Building, the maximum range of video and voice communication with acceptable quality (Minimum resolution: 352×288) was about 25 meters.

In our tests, for each measurement, 20 readings have been collected and the average values were used in the results. For example, the data in Table 4.1 were collected at the distance of 20 meters between two wireless devices.

Table 4.1 Sample of Throughputs in the Tests at the Same Position

| Throughput (Mbps) | | | | | | | | | |
|-------------------|--------|--------|--------|--------|--------|--------|--------|--------|-------|
| 12.459 | 11.571 | 11.359 | 11.383 | 11.593 | 11.71 | 12.585 | 11.365 | 11.964 | 12.3 |
| 12.388 | 12.352 | 11.927 | 11.655 | 11.951 | 12.516 | 12.679 | 12.549 | 12.272 | 12.39 |

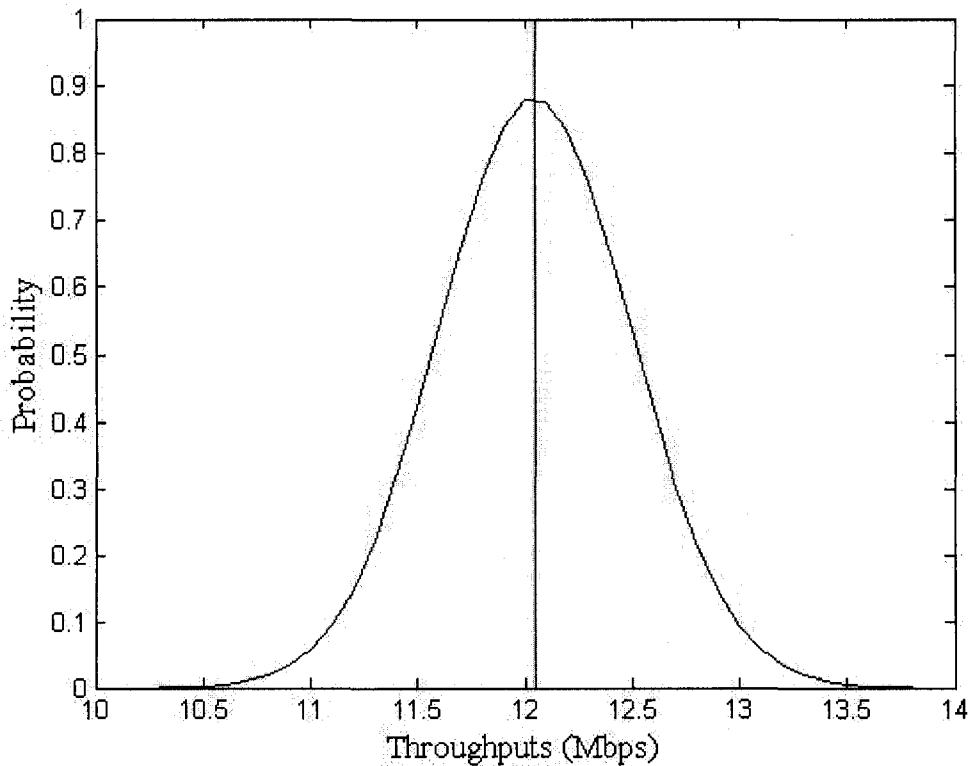


Figure 4.14 Probability Density Estimate Curve

The mean value of these data is 12.048, and the standard deviation is 0.452. According to these data and their mean and standard deviation we got the probability distribution estimate curve (Figure 4.14).

Table 4.2 Devices Used in Test-1

| Type | Device | Feature |
|--------------------|--------------------|--|
| Laptop 1 | Dell Precision M65 | Intel Core Duo T2700 2.33GHz, 1GB RAM, a, b, g type |
| Laptop 2 | Dell XPS M1210 | Intel Core Duo T2600 2.16GHz, 1GB RAM, a, b, g type |
| Laptop 3 | Toshiba Tecra A8 | Intel(R) Core™ Duo T2400, 1.83 GHz, 1GB RAM, a, b, g type |
| Wireless adapter 1 | D-link WUA-1340 | a, b, g type, Connectivity: USB |
| Digital camera | Logitech-3000 | Resolution : 640 × 480 @ 15 fps (video), Connectivity: USB |

4.4.2 TEST-1: TEST WITH BRIDGE NODE

As discussed in Section 3.2.5, we introduced our bridge test. Table 4.2 shows the devices used in this test.

In order to enlarge the communication range of two clients, we used bridge node as the intermediate node between the clients. Because different wireless adapters from various companies may not be compatible, we did many tests, and finally selected Laptop 2 and Wireless adapter 1 to make the bridge. First, we configured these two adapters into two different domains, and assigned their static IP addresses under ad-hoc mode. Then we let other wireless devices (Laptop 1 and Laptop 3) join these two domains separately in ad-hoc mode, and also assigned their static IP addresses. Finally, in Laptop 2, we combined its two wireless adapters into one bridge, and assigned its static IP address (details are given in Appendix B). Indoor testing can provide a realistic working environment (Jadhav et al., 2005), but the internal walls can weaken the strength of the

signal. We tested our *Ad-hoc Messenger* with the bridge node in the EV Building (Figure 4.10), and got the relationship between throughput and distance when moving in the corridor of the floor to avoid the effects of walls (Figure 4.15). In these tests, we let the system on laptop3 send a 100 KB file 100 times, and measured the average value of throughput at each testing position. From the results, we can see that the bridge enlarges the communication range of wireless adapters compared with Figure 4.13.

4.4.3 TEST-2: TEST USING AODV ROUTING PROTOCOL

In order to avoid the problems of using a bridge as explained in Section 3.2.5, we introduced another test using AODV routing protocol. In test-2, we tested this method on the ninth floor of the EV Building of Concordia downtown campus (Figure 4.10). Table 4.3 shows the main devices that we used in this test. In the test, we configured the WEP security protocol to ensure the security of our network.

Table 4.3 Devices Used in Test-2

| Type | Device | Feature |
|--------------------|--------------------------|--|
| Desktop 1 | IBM IntelliStation M Pro | Pentium(R) 4, 2.4 GHz, 768MB RAM |
| Laptop 1 | Dell Precision M65 | Intel Core Duo T2700 2.33GHz, 1GB RAM, a, b, g type |
| Laptop 2 | Dell XPS M1210 | Intel Core Duo T2600 2.16GHz, 1GB RAM, a, b, g type |
| Laptop 3 | Toshiba Tecra A8 | Intel(R) Core™ Duo T2400, 1.83 GHz, 1GB RAM, a, b, g type |
| Wireless adapter 2 | D-link WUA-1340 | a, b, g type, Connectivity: USB |
| Digital camera | Logitech-3000 | Resolution : 640 × 480 @ 15 fps (video), Connectivity: USB |

In this test, we used desktop 1 connected with wireless adapter 2 (working as the fixed node), and 2 laptops (working as the moving nodes). On each node, we installed and configured our *Ad-hoc Messenger* using AODV routing protocol to connect the whole wireless network. We distributed these moving nodes on the ninth floor of the EV Building. The system on each node worked well, and all of them could find and communicate with the destination node through our system.

In this test, within the range of 20 m, the moving node (Laptop 2) does not need the intermediate node (Laptop 1) to connect with the destination node (Desktop1). This is because the indoor communication range with high ideal connection speed (as Figure 4.12) of a single wireless adapter is about 20 meters. Furthermore, due to the interference of many factors inside the EV building (e.g. people, University's wireless signals, walls, etc.), intermediate nodes may not be selected in the routes.

As in test-1, we let the system on laptop3 send a 100 KB file 100 times, and measured the average value of throughput at each testing position. Figure 4.15 shows the results of our *Ad-hoc Messenger* with AODV routing protocol compared with the previous results in test-1 with a bridge. From the figure we can see that the overall performance of our system with AODV routing protocol is similar to that with a bridge. However, the throughput, when using a bridge, was slightly lower than when using AODV in most of the cases. This could be explained by the internal hardware communications between the two wireless adapters of the bridge. Few research results were found comparing the performance of bridging vs. AODV routing in ad-hoc networks. Jacob and Zhou (2004)

developed a bridging method at the data link layer. From the results of their simulation, they concluded that the packet delivery ratio of the bridging method is higher than that of AODV routing protocol. However, the average delay of bridging method is higher than that of AODV routing protocol. They explained that the later result (higher delays in the case of bridging) was against their expectation. Further study is needed in this area.

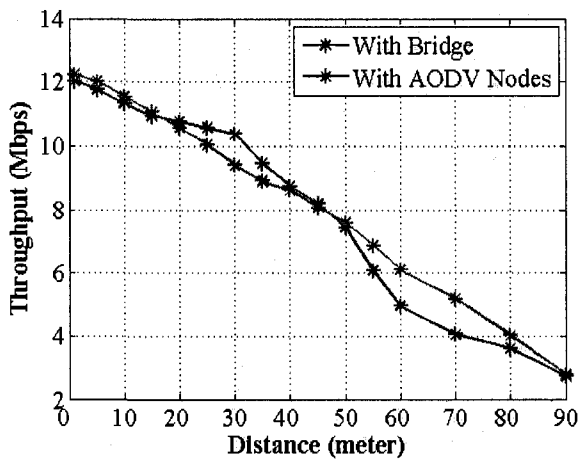


Figure 4.15 Throughput of Bridge and AODV Tests (without walls)

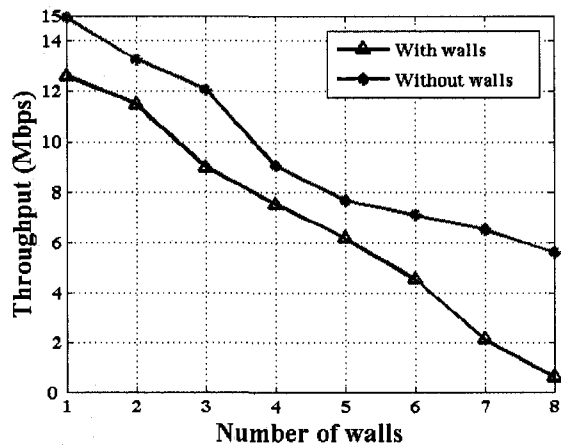


Figure 4.16 Testing with Walls and without Walls

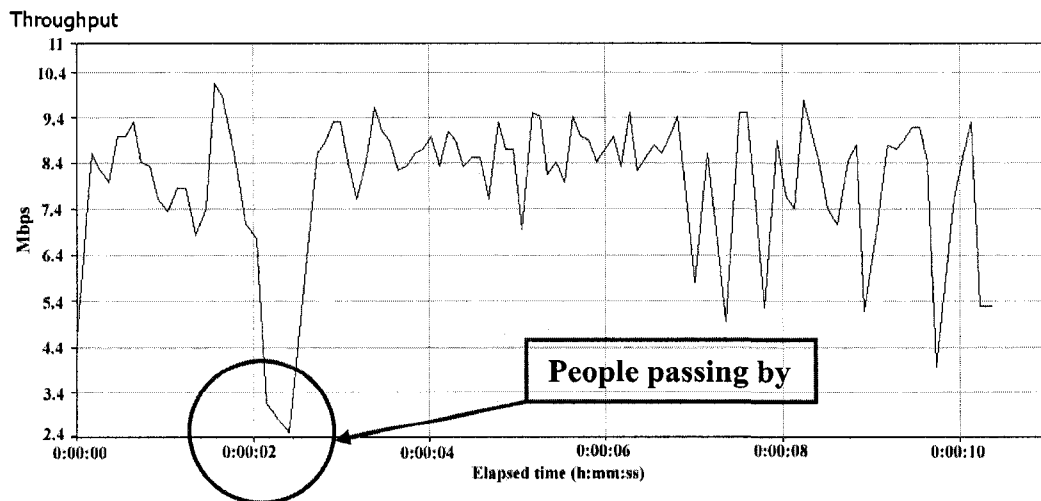


Figure 4.17 Example of Throughput Data When the Floor is not Crowded

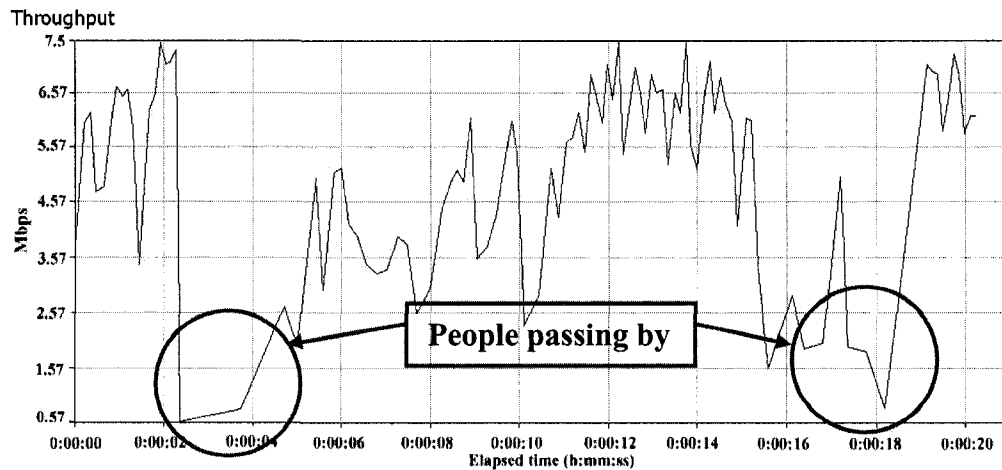


Figure 4.18 Example of Throughput Data When the Floor is Crowded

During the testing, we noticed that sometimes the data at the same position could vary widely, and we found that sometimes the throughput of the system could be almost zero because of the following factors: (1) The strong wireless signals of Concordia's wireless network and other electromagnetic waves from other labs in the EV Building. Sometimes these signals could occupy the channel of the ad-hoc network, which leads to zero throughput of our system; (2) Walls: We did some tests to check the effect of the interference of walls (Figure 4.16). The results show that the throughput with walls was much lower than the throughput without walls; (3) Human bodies (especially in the case of long range communication): Figures 4.17 and 4.18 show examples of the throughput data between two clients at a distance of about fifty meters from each other under two levels of number of people on the same floor. The average throughput values in these two figures are 7.75 Mbps and 3.96 Mbps, respectively. Moreover, Figure 4.18 shows that the movement of people near the wireless devices strongly affected the results. In addition,

we repeated test-1 and test-2 at different times (e.g. working day and holiday) in the EV building and found that the throughputs are different at different periods because of different levels of noise.

4.5 CLUSTERING SIMULATION RESULTS

As we reviewed in Section 2.6.3, many factors could affect the data accessibility. We modified the code of the *scenario* file, *tcl* file, and the *aodv* file based on different parameter, as was explained in Section 3.3, and run the simulation. Finally, the results from the trace file were extracted to study the effects on data accessibilities. In the simulation, we fixed the values of the following parameters (Table 3.2): total simulation time is 500 seconds; pause time is 2 seconds; data size is 1 KB; number of original data items per node is three; memory size of each node is 10 KB; replica allocation period is 100 seconds. In order to make the results more accurate, every simulation was run 5 times, and the average value was calculated as the final result. We analyzed the data accessibility based on the following four factors:

(1) Effect of area size

Six different area sizes were used: $50 \times 50 \text{ m}^2$, $100 \times 100 \text{ m}^2$, $200 \times 200 \text{ m}^2$, $400 \times 400 \text{ m}^2$, $500 \times 500 \text{ m}^2$, and $600 \times 600 \text{ m}^2$, and the other parameters were kept as the default values (Table 3.2). Figure 4.19(a) shows that the data accessibility depends on the area size. As the area size increases, the data accessibility decreases.

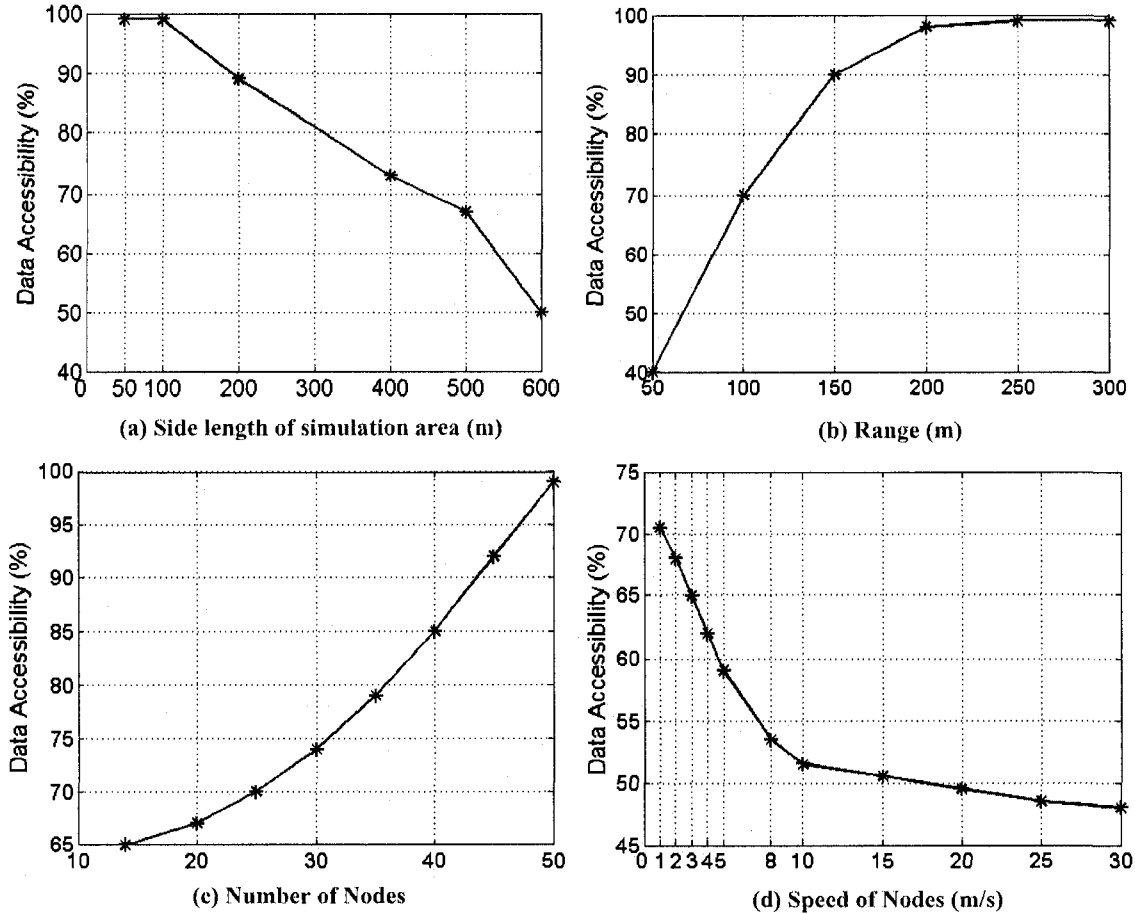


Figure 4.19 Effects of Area Size, Range, Node Number, and Speed

(2) Effect of wireless range

Six wireless ranges were used: 50 m, 100 m, 150 m, 200 m, 250 m, and 300 m, and the other parameters were kept as the default values (Table 3.2). In the real world testing, this could be realized by changing the power of the wireless adapter in the advanced

configuration of wireless adapter. Figure 4.19(b) shows that as the wireless range increases, the data accessibility increases.

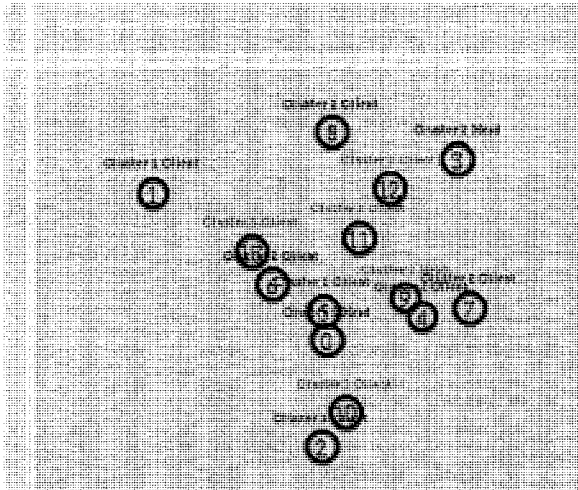
(3) Effect of the number of nodes

Eight node numbers were used: 14, 20, 25, 30, 35, 40, 45, and 50, and the other parameters were kept as the default values (Table 3.2). Figure 4.19(c) shows that as the number of nodes increases, the data accessibility increases.

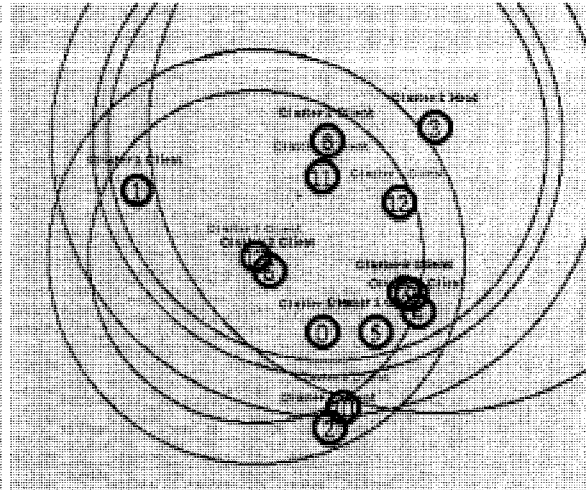
(4) Effect of node speed

Eleven speeds were used: 1 m/s, 2 m/s, 3m/s, 4 m/s, 5 m/s, 8 m/s, 10 m/s, 15 m/s, 20 m/s, 25 m/s, and 30 m/s, and the other parameters were kept as the default values (Table 3.2). In the real world testing, we can realize these movements by walking, using bicycles, or cars. Figure 4.19(d) shows that as the speed of the nodes increases, the data accessibility decreases.

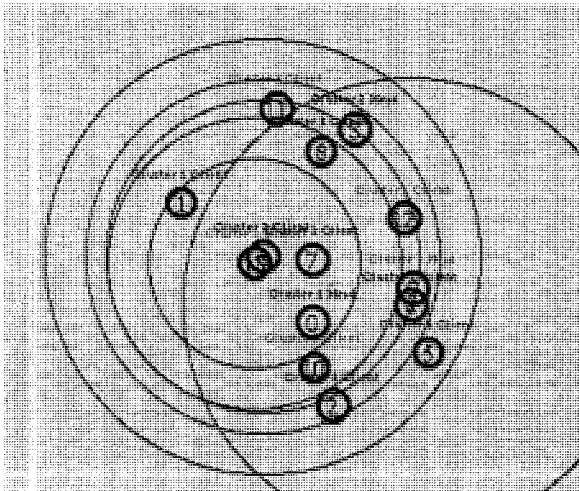
Figure 4.20 shows the screenshots of an animation. In this example, there are 3 clusters marked with different colors: red, green, and blue. During the simulation, all nodes are moving randomly, and sending data requests through their cluster heads. Because we used low-maintenance clustering scheme, if the distance between the node and its cluster head is too long (out of communication range), the data package will be dropped, which will lead to the decrease of data accessibility. For example, at time 300 second (Figure 4.20 (a)), all nodes of cluster 3 (node 9, node 10, node11, node 12, node 13) stayed together. As time goes by, node 11 moved far away from its cluster head (node 9) as shown in time 330 second (Figure 4.20 (b)) to time 390 second (Figure 4.20 (d)). During



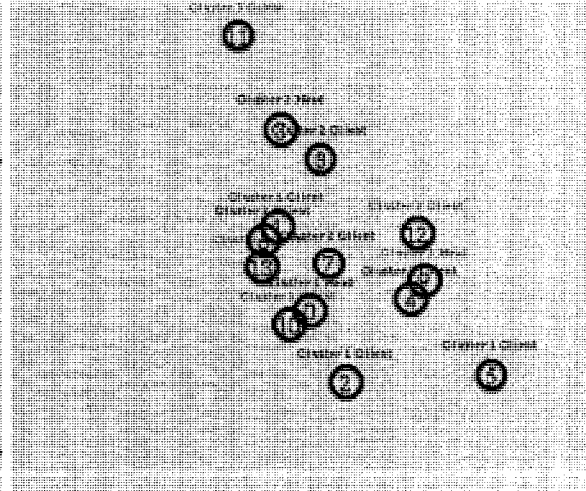
(a) Time 300 second



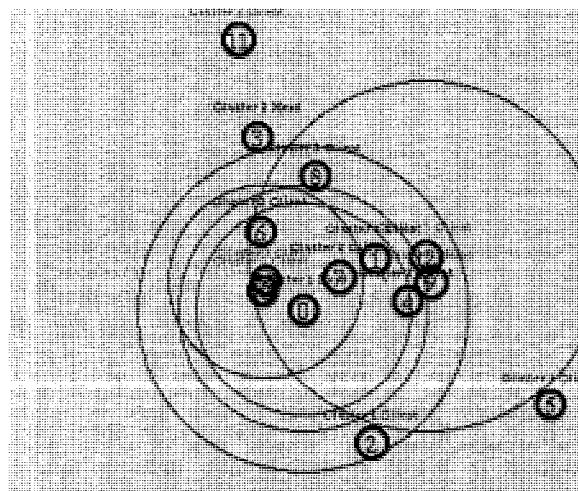
(b) Time 330 second



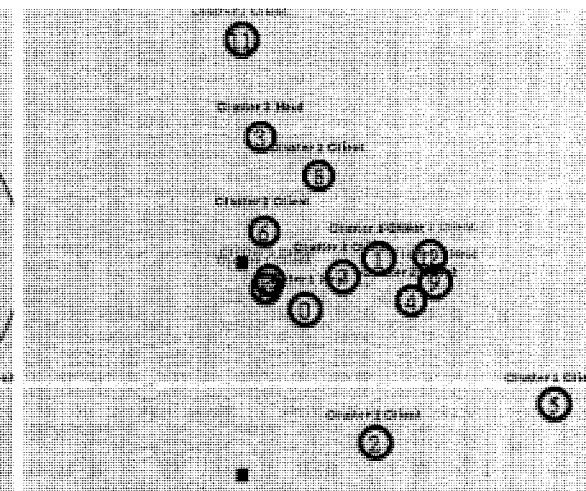
(c) Time 360 second



(d) Time 390 second



(e) Time 400 second



(f) Time 401 second

Figure 4.20 Screenshots of a Simulation Animation

this period, node 11 was in its cluster's communication range, so there are few data losses. From time 390 second (Figure 4.20 (d)), node 11 moved out of the communication range of its cluster. At time 100 second (Figure 4.20 (e)) and time 101 second (Figure 4.20 (f)), more and more data packages were dropped, and the data accessibility of the whole network decreased.

4.6 SUMMARY AND CONCLUSIONS

This chapter described the implementation of our proposed approach and methods discussed in Chapter 3. The software development tools were selected to integrate several information technologies in the prototype system. A prototype system was developed for testing the communication of ad-hoc networks. The validity of the proposed approach and framework are demonstrated by examining two tests: test with a bridge and test with AODV routing protocol.

In the testing, we tested our system in two different tests: with a bridge, and with AODV routing protocol. The overall results of the tests showed that our *Ad-hoc Messenger* was working well in the tests. By analyzing the data we got from large number of tests, we got the indoor and outdoor ideal connection speed of the wireless adapter (g type), and compared our *Ad-hoc Messenger* and another tool (Ixchariot), which indicated the accuracy of our system. Furthermore, by comparing the results of the two tests, we found that using AODV routing protocol is more suitable than using a bridge for ad-hoc wireless networks. Finally, according to many failed tests, we concluded that many

factors could affect the quality of ad-hoc wireless networks such as noise signals, walls, and human bodies.

The real-time simulation of the CBRA protocol was implemented with Ns2 in Linux environment. In the simulation, the effects on data accessibility were studied. The following results were obtained from the simulation: (1) The data accessibility decreases with the increase of the area size and the speed of the nodes; (2) The data accessibility increases with the increase of wireless range and the number of nodes.

CHAPTER 5 SUMMARY, CONCLUSIONS, AND FUTURE WORK

5.1 SUMMARY

As we reviewed in Chapter 2, many communication technologies are used on a daily basis for on-site communication and collaboration. However, many of them have some disadvantages that may not be suitable for on-site engineering applications. Furthermore, several routing protocols for ad-hoc networks and some ad-hoc test-beds were presented. However, the research about the efficient usage of ad-hoc networking in engineering applications is still limited.

This research presented a new approach to investigate problems related to deploying ad-hoc wireless networks for supporting on-site communication and collaboration. Several modes of communication which are common in on-site applications have been considered including location information, text messaging, voice and video communications, and file transmission. These modes have been integrated in a prototype system which can be used for testing the performance based on available ad-hoc network protocols and using different types of mobile devices. Furthermore, the prototype system was tested large number of times with a bridge and with AODV routing protocol to test its practicality and stability.

Finally, the CBRA protocol based on replication and clustering was simulated using Ns2 and tested to investigate the effect on data accessibility. The simulated results of the performance of this protocol using different scenarios of ad-hoc clusters were analyzed.

The results showed the impact of the area size, wireless range, number of nodes, and node speed on data accessibility.

5.2 CONCLUSIONS AND CONTRIBUTIONS

The conclusions and contributions of this research are grouped into the following items:

- (1) A new testing approach was proposed to investigate problems related to deploying ad-hoc wireless networks for supporting on-site communication and collaboration. Several modes of communication which are common in on-site applications have been considered including location information, text messaging, voice and video communications, and file transmission. A system, *Ad-hoc Messenger*, which can support several common modes of on-site communications was designed and implemented using Java and AODV routing. A Java application, named Jadhoc was studied and combined with our prototype system. Two types of tests were considered by using different routing methods: a bridge (manual routing), and self-organized routing (AODV routing).
- (2) The different functions of the system were tested successfully (position and text messaging, voice and video communications, throughput testing, and routing).
- (3) Several wireless devices (laptops, tablet PCs, and different type of wireless adapters) were used to investigate the effects of the distance, environment (indoor, outdoor, noise), and routing methods (bridge or AODV routing) on the throughput. The overall results of the tests showed that our *Ad-hoc Messenger* was working well on the tests.

By analyzing the data we got from large number of tests, we got the indoor and outdoor ideal connection speed of the wireless adapter (g type), and compared of our *Ad-hoc Messenger* and another tool (Ixchariot), which indicated the accuracy of our system. Furthermore, by comparing the results of the two tests, we found that using AODV routing protocol is much more suitable than using a bridge for ad-hoc wireless networks. Finally, according to many failed tests, we concluded that many factors could affect the quality of ad-hoc wireless networks such as noise signals and electric waves, walls, and human bodies.

- (4) A simulation model based on CBRA was used to test data accessibility. Different simulation scenarios were applied based on a large number of simulation runs to study the effects of area size, wireless range, number and speed of nodes on data accessibility. The following results were obtained from the simulation: (1) The data accessibility decreases with the increase of the area size and the speed of the nodes; (2) The data accessibility increases with the increase of wireless range and the number of nodes.

5.3 FUTURE WORK

While pursuing this research, several limitations have been identified related to the requirements and the performance of the developed methods and techniques. Future work will consider the following issues:

- (1) Further development of the Ad-hoc Messenger system for simulating the CBRA protocol in real test cases.
- (2) The Ad-hoc Messenger video communication function is at present a point to point system. Future work will extend it to support video broadcasting and multimedia conferencing based on the mixer method (Khedher et al. 2006).
- (3) Studying the effect of using antennas to increase the range of wireless communication.
- (4) Considering other issues of MANET, such as security.

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APPENDIX A SOFTWARE REQUIREMENTS AND INSTALLATION GUIDE OF THE PROTOTYPE SYSTEM

SOFTWARE REQUIREMENTS:

- (1) Borland JBuilder 2006 Enterprise: used to develop and run the prototype system of *Ad-hoc Messenger*;
- (2) Windows XP: used as the operating system.

INSTALLATION GUIDE:

Install the following software in the specified order:

1. Because the position messaging function is combined with our 3D maps of Concordia downtown campus, the installation guide of this part please read the thesis of Yongxin Hu, “Mobile Location-Based Bridge Inspection Decision-Support System”, Appendix F. (Hu, 2006)

2. Drivers of the digital camera are required, which are used for the video communication.

3. JMF (Java Media Framework API) – version 2.1.1

Download the library form: <http://java.sun.com/products/java-media/jmf/2.1.1/download.html> and install it after you install the driver of the camera.

4. Jadhoc (AODV routing protocol) – version 0.2

Download the library form: <http://www.aodv.org/modules.php?op=modload&name=UpDownload&file=index&req=viewdownload&cid=2> and install it according to the following instructions:

- (1) Install WinPcap for Windows (<http://winpcap.polito.it>) and run the application WinPcap.exe;
- (2) Install Jpcap (<http://netresearch.ics.uci.edu/kfujii/jpcap/doc/index.html>) and add its path to the JBuilder’s library;
- (3) Copy all application (*.exe) files in .\windows-xp-tools directory to the system commands directory specified in the JAdhoc configuration file. (C:\Windows\system32);
- (4) Set environment for JAdhoc, set JADHOC=C:\jadhoc-0.2, and set CLASSPATH=%JADHOC%;%JADHOC%\utils;%CLASSPATH%.

APPENDIX B: HARDWARE REQUIREMENTS AND CONFIGURATION GUIDE OF THE PROTOTYPE SYSTEM

HARDWARE REQUIREMENTS:

- (1) Desktops: the basic feature should be Pentium(R) 4, 2.0 GHz, 512MB RAM or higher; they are combined with USB wireless adapters working as the fixed nodes.
- (2) Tablet PCs and laptops: the basic feature should be Centrino (M), 1GHz, 512MB RAM or higher, with b or g type wireless adapter; they are working as the moving nodes.
- (3) PDAs: the basic feature should be Intel XScale400MHz, 64MB RAM or higher, with b or g type wireless adapter; they are working as the moving nodes.
- (4) Digital Cameras: the basic feature should be $640 \times 480 @ 15 \text{ fps}$ (video) or higher; they are used to capture the live video.
- (5) Ear phones and microphones: use combined ear phone and microphone in order to reduce the load.

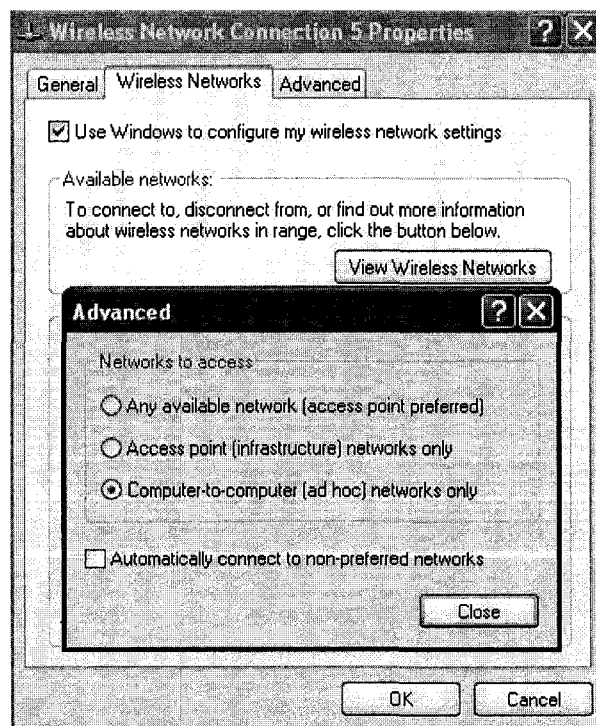


Figure B.1 Advanced Configuration of Ad-hoc

CONFIGURATION GUIDE:

In the advanced configuration of the wireless adapter properties, “networks to access” should be changed from “Any available network (access point preferred)” to “Computer-to-computer (ad-hoc) networks only” (Figure B.1).

Furthermore, if the wireless device is the first device in the ad-hoc wireless network, a new wireless network domain should be initialized (e.g. in Figure 3.4, a new network domain named “Dlink”). Accordingly, Wired Equivalent Privacy (WEP) option should be added to the new network properties in order to provide security to the ad-hoc wireless network. In the properties of the new network, the “Network Authentication” should be changed to “Open”, and the “Data encryption” should be changed to “WEP”. Then the user can input the private “Network key” (Figure B.2).

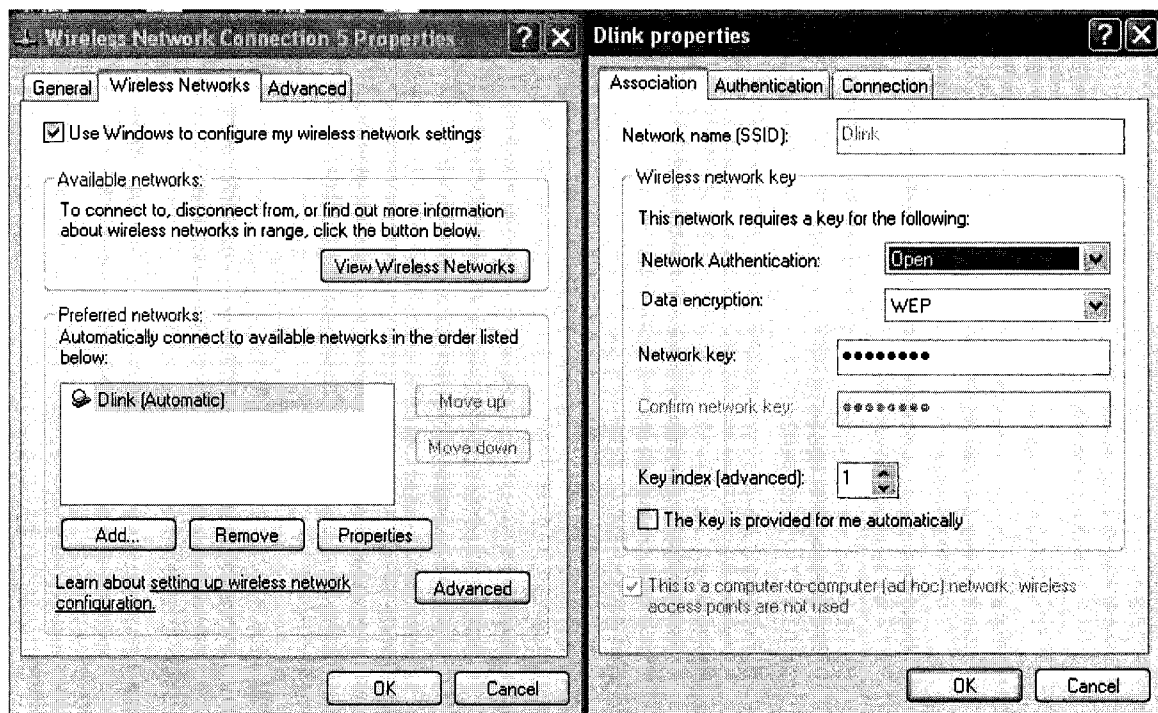


Figure B.2 Configuration of Wireless Network

If the wireless device is not the first device in the ad-hoc network, after the ad-hoc mode was changed, the window system can detect the available ad-hoc networks (Figure B.3), then the user can select which ad-hoc wireless network should join, and input the correct network key (Figure B.4).

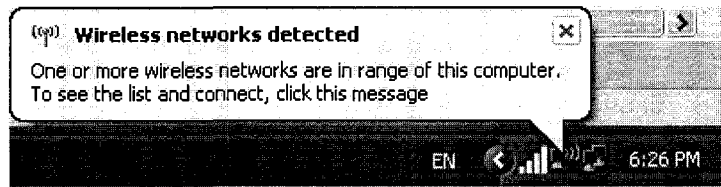


Figure B.3 Ad-hoc Wireless Network was Detected

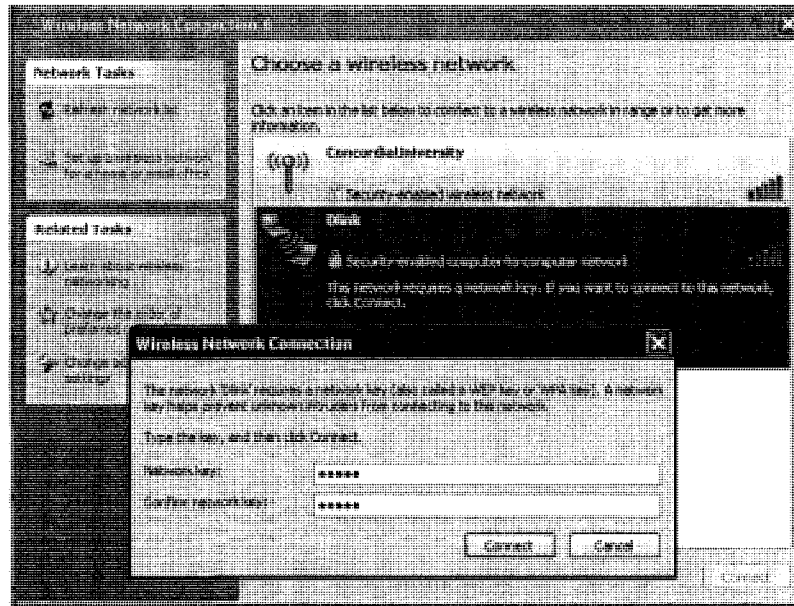


Figure B.4 Joining an Existing Ad-hoc Wireless Network

There are two types of test-beds in this research, and each one uses different wireless devices and connecting methods. We explain the detailed installation as follows:

1. Test-bed with bridge

(1) Bridge installation

The mobile computer that works as the bridge should be a very powerful device which has one internal wireless adapter and can install at least one external wireless adapter. First, we configured these two wireless adapters into two different domains, and let them get their static IP address under ad-hoc mode. Then we let other wireless devices join these two domains separately in ad-hoc mode, and also get their static IP address. Finally, on the bridge, we combined its two wireless adapters into one bridge, and let it get its static IP address.

(2) IP address

Every node in the network should have its unique IP address, either C class, or B class (depends on the number of the wireless devices), but all of the nodes should be

in the same subnet domain. Usually, we assign the gateway IP address to the bridge node.

Examples:

C Class subnet:

Bridge (Gateway): IP address: 192.168.16.1
Subnet mask: 255.255.255.0
Gateway: 192.168.16.1

Other nodes: IP address: 192.168.16.* (2-254)
Subnet mask: 255.255.255.0
Gateway: 192.168.16.1

B Class subnet:

Bridge (Gateway): IP address: 169.254.0.1
Subnet mask: 255.255.0.0
Gateway: 169.254.0.1

Other nodes: IP address: 169.254.*.*
Subnet mask: 255.255.0.0
Gateway: 169.254.0.1

2. Test-bed with AODV routing protocol

In this test-bed, every node could become the intermediate node, so every one of them should install our prototype system, *Ad-hoc Messenger* (which includes JAdhoc function).

(1) IP address

Each node in this test-bed could be assigned to the same subnet or to a different subnet (Depending on the number of the wireless devices), but the gateway IP address could not be used. We give examples of how we assign IP addresses to the nodes in our testing as follows:

Node 1: IP address: 192.168.12.2
Subnet mask: 255.255.255.0
Gateway: 192.168.12.1

Node 2: IP address: 192.168.16.2
Subnet mask: 255.255.255.0
Gateway: 192.168.16.1

Node 3: IP address: 192.168.8.2

Subnet mask: 255.255.255.0
Gateway: 192.168.8.1

Node 4: IP address: 192.168.10.2
Subnet mask: 255.255.255.0
Gateway: 192.168.10.1

Node 5: IP address: 192.168.6.2
Subnet mask: 255.255.255.0
Gateway: 192.168.6.1

(2) Configuration of Jadhoc

In our system, there is another Java application named ListIfc, which is used to detect the network adapter's device ID. After running this application, the system will display the device ID of the currently used network adapters, the user should find the one that belong to the wireless adapter, for example

"\Device\NPF_{E786257A-A36A-4BA1-9CE9-8C238C370E92}"

Then the user should copy this device ID to the IfaceName and LoopbackIfaceName in the configuration table of Jadhoc (Figure B.5). Furthermore, input the IP address and IPAddressGateway same as the configuration of the wireless adapter (Figure B.5).

| Parameter | Value |
|-------------------|--|
| ExecutionMode | GUI |
| OSInUse | Windows |
| IPVersion | IPv4 |
| IPAddress | 192.168.12.2 |
| IfaceName | \Device\NPF_{E786257A-A36A-4BA1-9C...} |
| IPAddressGateway | 192.168.12.1 |
| LoopbackIfaceName | \Device\NPF_{E786257A-A36A-4BA1-9C...} |
| LoggingStatus | Yes |
| LoggingLevel | 3 |
| LogFile | .\jadhoc.log |
| PathToSystemCmds | c:\windows\system32 |
| OnlyDestination | Yes |

Update Cancel

Figure B.5 Configuration of JAdhoc

APPENDIX C: SIMULATION TOOLS AND INSTALLATION GUIDE

The simulation part of this research is the continuation of one of our previous colleague's work. Because he deleted all the system on his desktop, we had to spend a lot of time to install and configure the system. However, because both the Linux and Ns2 updated to new versions, we had to solve compatibility problems that new version of Ns2 could not run on new version of Linux. During this period, we also found other problems, for example, the previous coding has some problems, and could not be run.

In the following we will explain the detailed information, so the future researchers can continue this work smoothly.

1. Installation of Linux

We used Fedora Linux Core 4.

2. Installation of Ns2

We used version Ns2.28 with the patch file for Fedora Linux Core 4.

In the windows interface of Linux:

- (1) Unzip the file named "ns2.tar.gz" into the folder "ns".
- (2) Run the Linux terminal (Figure C.1).
- (3) Go to the directory "ns/ns-allinone-2.28/", then type "./install".
- (4) Copy the patch file named "ns2P.patch" to ns/ns-allinone-2.28/ns-2.28.
- (5) Configure the environment setting following the instruction of the terminal after the installation is complete and successful.
- (6) In the directory of ns/ns-allinone-2.28/ns-2.28, type "make clean".
- (7) In the directory of ns/ns-allinone-2.28/ns-2.28, type "patch -p0 < ns2P.patch".
- (8) Go to ns/ns-allinone-2.28/ns-2.28 and type "./configure", then "make" command.
- (9) The installation should be fine and to make sure that there will be no error when you run any simulation: go to ns/ns-allinone-2.28/ns-2.28 and type "./validate".

3. Example source code of modified version of the simulation code developed in (Mahboob, 2005)

Clustering.tcl

```
#####Modified by Linchuan Yang#####
=====
# Define options
#
=====
set val(chan) Channel/WirelessChannel
set val(prop) Propagation/TwoRayGround
set val(netif) Phy/WirelessPhy
set val(mac) Mac/802_11
set val(ifq) Queue/DropTail/PriQueue
set val(ll) LL
set val(ant) Antenna/OmniAntenna
set val(x) 300 ;# X dimension of the
topography
set val(y) 300 ;# Y dimension of
the topography
set val(ifqlen) 100 ;# max
packet in ifq
set val(seed) 0.0
set val(adhocRouting) AODV
set val(nn) 14 ;# how many
nodes are simulated
set val(cp) ""
set val(sc) "/default-scene-14-cluster"
set val(stop) 500.0 ;#
simulation time

#
=====
# Main Program
#
=====

Phy/WirelessPhy set Pt_ 10.5872e-3.1
#Mac/802_11 set dataRate_ 11e6

#
# Initialize Global Variables
#

# create simulator instance

set ns_ [new Simulator]

# set up for hierarchical routing
#Sns_node-config -addressType hierarchical
AddrParams set domain_num_ 1 ;#
number of domains
lappend cluster_num 3 ;# number
of clusters in each domain
AddrParams set cluster_num_ $cluster_num
lappend eilastlevel 4 5 5 ;# number of nodes in
each cluster
AddrParams set nodes_num_ $eilastlevel ;# of each
domain

# setup topography object

set topo [new Topography]
```

```
# create trace object for ns and nam

set tracefd [open replication14.tr w]
$ns_ trace-all $tracefd
#$ns_ use-newtrace

set namtrace [open replication14.nam w]
$ns_ trace-all $tracefd
$ns_ namtrace-all-wireless $namtrace $val(x) $val(y)

# define topology
$topo load_flatgrid $val(x) $val(y)

# Create God

set god_ [create-god $val(nn)]

set channel1 [new $val(chan)]

# define how node should be created
# global node setting

$ns_ node-config -adhocRouting $val(adhocRouting) \
                -llType $val(ll) \
                -macType $val(mac) \
                -ifqType $val(ifq) \
                -ifqLen $val(ifqlen) \
                -antType $val(ant) \
                -propType $val(prop) \
                -phyType $val(netif) \
                -channel $channel1 \
                -topoInstance $topo \
                -agentTrace ON \
                -routerTrace ON \
                -macTrace ON \

# Create the specified number of nodes [$val(nn)]
and "attach" them
# to the channel.

for {set j 0} {$j < $val(nn)} {incr j} {
    set node_($j) [$ns_ node]
}

$node_(0) label "Cluster 1 Head"
$node_(0) label-color "red"
$node_(0) shape "box"

$node_(1) label "Cluster 1 Client"
$node_(1) label-color "red"

$node_(2) label "Cluster 1 Client"
$node_(2) label-color "red"

$node_(5) label "Cluster 1 Client"
$node_(5) label-color "red"

$node_(3) label "Cluster 2 Head"
$node_(3) label-color "blue"
$node_(3) shape "box"
```

```

$node_(4) label "Cluster 2 Client"
$node_(4) label-color "blue"

$node_(6) label "Cluster 2 Client"
$node_(6) label-color "blue"

$node_(7) label "Cluster 2 Client"
$node_(7) label-color "blue"

$node_(8) label "Cluster 2 Client"
$node_(8) label-color "blue"

$node_(9) label "Cluster 3 Head"
$node_(9) label-color "green"
$node_(9) shape "box"

$node_(10) label "Cluster 3 Client"
$node_(10) label-color "green"

$node_(11) label "Cluster 3 Client"
$node_(11) label-color "green"

$node_(12) label "Cluster 3 Client"
$node_(12) label-color "green"

$node_(13) label "Cluster 3 Client"
$node_(13) label-color "green"

# Traffic

for {set c 0} {$c <= 13} {incr c} {
    set agent_($c) [new Agent/Ping]
}

for {set d 0} {$d <= 13} {incr d} {
    $ns_ attach-agent $node_($d)
    $agent_($d)
}

# Connecting Agents

for {set a 0} {$a <= 13} {incr a} {
    for {set b 0} {$b <= 13} {incr b} {
        $ns_ connect $agent_($a) $agent_($b)
    }
}

#Schedule Events

for {set p 0} {$p <= 13} {incr p} {
    set e 0.0
    while {$e <= 500} {
        $ns_ at $e "$agent_($p) send0"
        set e [expr $e - (1/0.41)*log(rand())]
    }
}

# At 99 Sec.

# CM to CH

set ping_(0) [new Agent/Ping]
$ns_ attach-agent $node_(0) $ping_(0)
set ping_(1) [new Agent/Ping]
$ns_ attach-agent $node_(1) $ping_(1)

```

```

#Connect the two agents
$ns_ connect $ping_(0) $ping_(1)
#Schedule events
$ns_ at 99.0 "$ping_(1) send"

set ping_(5) [new Agent/Ping]
$ns_ attach-agent $node_(5) $ping_(5)
#Connect the two agents
$ns_ connect $ping_(5) $ping_(0)
#Schedule events
$ns_ at 99.0 "$ping_(5) send"

set ping_(2) [new Agent/Ping]
$ns_ attach-agent $node_(2) $ping_(2)
#Connect the two agents
$ns_ connect $ping_(2) $ping_(0)
#Schedule events
$ns_ at 99.0 "$ping_(2) send"

set ping_(3) [new Agent/Ping]
$ns_ attach-agent $node_(3) $ping_(3)
set ping_(4) [new Agent/Ping]
$ns_ attach-agent $node_(4) $ping_(4)
#Connect the two agents
$ns_ connect $ping_(4) $ping_(3)
#Schedule events
$ns_ at 99.0 "$ping_(4) send"

set ping_(6) [new Agent/Ping]
$ns_ attach-agent $node_(6) $ping_(6)
#Connect the two agents
$ns_ connect $ping_(6) $ping_(3)
#Schedule events
$ns_ at 99.0 "$ping_(6) send"

set ping_(7) [new Agent/Ping]
$ns_ attach-agent $node_(7) $ping_(7)
#Connect the two agents
$ns_ connect $ping_(7) $ping_(3)
#Schedule events
$ns_ at 99.0 "$ping_(7) send"

set ping_(8) [new Agent/Ping]
$ns_ attach-agent $node_(8) $ping_(8)
#Connect the two agents
$ns_ connect $ping_(8) $ping_(3)
#Schedule events
$ns_ at 99.0 "$ping_(8) send"

set ping_(9) [new Agent/Ping]
$ns_ attach-agent $node_(9) $ping_(9)
set ping_(10) [new Agent/Ping]
$ns_ attach-agent $node_(10) $ping_(10)
#Connect the two agents
$ns_ connect $ping_(10) $ping_(9)
#Schedule events
$ns_ at 99.0 "$ping_(10) send"

set ping_(11) [new Agent/Ping]
$ns_ attach-agent $node_(11) $ping_(11)
#Connect the two agents
$ns_ connect $ping_(11) $ping_(9)
#Schedule events
$ns_ at 99.0 "$ping_(11) send"

set ping_(12) [new Agent/Ping]
$ns_ attach-agent $node_(12) $ping_(12)
#Connect the two agents
$ns_ connect $ping_(12) $ping_(9)
#Schedule events

```

```

$ns_ at 99.0 "$ping_(12) send"

set ping_(13) [new Agent/Ping]
$ns_ attach-agent $node_(13) $ping_(13)
#Connect the two agents
$ns_ connect $ping_(13) $ping_(9)
#Schedule events
$ns_ at 99.0 "$ping_(13) send"

# CH to CH

$ns_ connect $ping_(0) $ping_(3)
$ns_ connect $ping_(0) $ping_(9)
#Schedule events
$ns_ at 99.3 "$ping_(0) send1"

$ns_ connect $ping_(3) $ping_(0)
$ns_ connect $ping_(3) $ping_(9)
#Schedule events
$ns_ at 99.3 "$ping_(3) send1"

$ns_ connect $ping_(9) $ping_(0)
$ns_ connect $ping_(9) $ping_(3)
#Schedule events
$ns_ at 99.3 "$ping_(9) send1"

# CH to CM

#Schedule events
$ns_ at 99.5 "$ping_(0) send2"
$ns_ at 99.5 "$ping_(3) send2"
$ns_ at 99.5 "$ping_(9) send2"

# CH to CH

$ns_ connect $ping_(0) $ping_(3)
$ns_ connect $ping_(0) $ping_(9)
#Schedule events
$ns_ at 99.5 "$ping_(0) send3"

$ns_ connect $ping_(3) $ping_(0)
$ns_ connect $ping_(3) $ping_(9)
#Schedule events
$ns_ at 99.5 "$ping_(3) send3"

$ns_ connect $ping_(9) $ping_(0)
$ns_ connect $ping_(9) $ping_(3)
#Schedule events
$ns_ at 99.5 "$ping_(9) send3"

# CH to CM

#Schedule events
$ns_ at 99.7 "$ping_(0) send4"
$ns_ at 99.7 "$ping_(3) send4"
$ns_ at 99.7 "$ping_(9) send4"
# Test - Access Log of Data

# At 199 Sec.

# CM to CH

set ping_(0) [new Agent/Ping]
$ns_ attach-agent $node_(0) $ping_(0)
set ping_(1) [new Agent/Ping]
$ns_ attach-agent $node_(1) $ping_(1)
#Connect the two agents
$ns_ connect $ping_(0) $ping_(1)
#Schedule events

```

```

$ns_ at 199.0 "$ping_(1) send"

set ping_(5) [new Agent/Ping]
$ns_ attach-agent $node_(5) $ping_(5)
#Connect the two agents
$ns_ connect $ping_(5) $ping_(0)
#Schedule events
$ns_ at 199.0 "$ping_(5) send"

set ping_(2) [new Agent/Ping]
$ns_ attach-agent $node_(2) $ping_(2)
#Connect the two agents
$ns_ connect $ping_(2) $ping_(0)
#Schedule events
$ns_ at 199.0 "$ping_(2) send"

set ping_(3) [new Agent/Ping]
$ns_ attach-agent $node_(3) $ping_(3)
set ping_(4) [new Agent/Ping]
$ns_ attach-agent $node_(4) $ping_(4)
#Connect the two agents
$ns_ connect $ping_(4) $ping_(3)
#Schedule events
$ns_ at 199.0 "$ping_(4) send"

set ping_(6) [new Agent/Ping]
$ns_ attach-agent $node_(6) $ping_(6)
#Connect the two agents
$ns_ connect $ping_(6) $ping_(3)
#Schedule events
$ns_ at 199.0 "$ping_(6) send"

set ping_(7) [new Agent/Ping]
$ns_ attach-agent $node_(7) $ping_(7)
#Connect the two agents
$ns_ connect $ping_(7) $ping_(3)
#Schedule events
$ns_ at 199.0 "$ping_(7) send"

set ping_(8) [new Agent/Ping]
$ns_ attach-agent $node_(8) $ping_(8)
#Connect the two agents
$ns_ connect $ping_(8) $ping_(3)
#Schedule events
$ns_ at 199.0 "$ping_(8) send"

set ping_(9) [new Agent/Ping]
$ns_ attach-agent $node_(9) $ping_(9)
set ping_(10) [new Agent/Ping]
$ns_ attach-agent $node_(10) $ping_(10)
#Connect the two agents
$ns_ connect $ping_(10) $ping_(9)
#Schedule events
$ns_ at 199.0 "$ping_(10) send"

set ping_(11) [new Agent/Ping]
$ns_ attach-agent $node_(11) $ping_(11)
#Connect the two agents
$ns_ connect $ping_(11) $ping_(9)
#Schedule events
$ns_ at 199.0 "$ping_(11) send"

set ping_(12) [new Agent/Ping]
$ns_ attach-agent $node_(12) $ping_(12)
#Connect the two agents
$ns_ connect $ping_(12) $ping_(9)
#Schedule events
$ns_ at 199.0 "$ping_(12) send"

set ping_(13) [new Agent/Ping]

```

```

$ns_ attach-agent $node_(13) $ping_(13)
#Connect the two agents
$ns_ connect $ping_(13) $ping_(9)
#Schedule events
$ns_ at 199.0 "$ping_(13) send"

```

```

# CH to CH

```

```

$ns_ connect $ping_(0) $ping_(3)
$ns_ connect $ping_(0) $ping_(9)
#Schedule events
$ns_ at 199.3 "$ping_(0) send1"

```

```

$ns_ connect $ping_(3) $ping_(0)
$ns_ connect $ping_(3) $ping_(9)
#Schedule events
$ns_ at 199.3 "$ping_(3) send1"

```

```

$ns_ connect $ping_(9) $ping_(0)
$ns_ connect $ping_(9) $ping_(3)
#Schedule events
$ns_ at 199.3 "$ping_(9) send1"

```

```

# CH to CM

```

```

#Schedule events
$ns_ at 199.5 "$ping_(0) send2"
$ns_ at 199.5 "$ping_(3) send2"
$ns_ at 199.5 "$ping_(9) send2"

```

```

# CH to CH

```

```

$ns_ connect $ping_(0) $ping_(3)
$ns_ connect $ping_(0) $ping_(9)
#Schedule events
$ns_ at 199.5 "$ping_(0) send3"

```

```

$ns_ connect $ping_(3) $ping_(0)
$ns_ connect $ping_(3) $ping_(9)
#Schedule events
$ns_ at 199.5 "$ping_(3) send3"

```

```

$ns_ connect $ping_(9) $ping_(0)
$ns_ connect $ping_(9) $ping_(3)
#Schedule events
$ns_ at 199.5 "$ping_(9) send3"

```

```

# CH to CM

```

```

#Schedule events
$ns_ at 199.7 "$ping_(0) send4"
$ns_ at 199.7 "$ping_(3) send4"
$ns_ at 199.7 "$ping_(9) send4"

```

```

# At 299 Sec.

```

```

# CM to CH

```

```

set ping_(0) [new Agent/Ping]
$ns_ attach-agent $node_(0) $ping_(0)
set ping_(1) [new Agent/Ping]
$ns_ attach-agent $node_(1) $ping_(1)
#Connect the two agents
$ns_ connect $ping_(0) $ping_(1)
#Schedule events
$ns_ at 299.0 "$ping_(1) send"

```

```

set ping_(5) [new Agent/Ping]

```

```

$ns_ attach-agent $node_(5) $ping_(5)
#Connect the two agents
$ns_ connect $ping_(5) $ping_(0)
#Schedule events
$ns_ at 299.0 "$ping_(5) send"

```

```

set ping_(2) [new Agent/Ping]
$ns_ attach-agent $node_(2) $ping_(2)
#Connect the two agents
$ns_ connect $ping_(2) $ping_(0)
#Schedule events
$ns_ at 299.0 "$ping_(2) send"

```

```

set ping_(3) [new Agent/Ping]
$ns_ attach-agent $node_(3) $ping_(3)
set ping_(4) [new Agent/Ping]
$ns_ attach-agent $node_(4) $ping_(4)
#Connect the two agents
$ns_ connect $ping_(4) $ping_(3)
#Schedule events
$ns_ at 299.0 "$ping_(4) send"

```

```

set ping_(6) [new Agent/Ping]
$ns_ attach-agent $node_(6) $ping_(6)
#Connect the two agents
$ns_ connect $ping_(6) $ping_(3)
#Schedule events
$ns_ at 299.0 "$ping_(6) send"

```

```

set ping_(7) [new Agent/Ping]
$ns_ attach-agent $node_(7) $ping_(7)
#Connect the two agents
$ns_ connect $ping_(7) $ping_(3)
#Schedule events
$ns_ at 299.0 "$ping_(7) send"

```

```

set ping_(8) [new Agent/Ping]
$ns_ attach-agent $node_(8) $ping_(8)
#Connect the two agents
$ns_ connect $ping_(8) $ping_(3)
#Schedule events
$ns_ at 299.0 "$ping_(8) send"

```

```

set ping_(9) [new Agent/Ping]
$ns_ attach-agent $node_(9) $ping_(9)
set ping_(10) [new Agent/Ping]
$ns_ attach-agent $node_(10) $ping_(10)
#Connect the two agents
$ns_ connect $ping_(10) $ping_(9)
#Schedule events
$ns_ at 299.0 "$ping_(10) send"

```

```

set ping_(11) [new Agent/Ping]
$ns_ attach-agent $node_(11) $ping_(11)
#Connect the two agents
$ns_ connect $ping_(11) $ping_(9)
#Schedule events
$ns_ at 299.0 "$ping_(11) send"

```

```

set ping_(12) [new Agent/Ping]
$ns_ attach-agent $node_(12) $ping_(12)
#Connect the two agents
$ns_ connect $ping_(12) $ping_(9)
#Schedule events
$ns_ at 299.0 "$ping_(12) send"

```

```

set ping_(13) [new Agent/Ping]
$ns_ attach-agent $node_(13) $ping_(13)
#Connect the two agents
$ns_ connect $ping_(13) $ping_(9)

```

```

#Schedule events
$ns_ at 299.0 "$ping_(13) send"

# CH to CH

$ns_ connect $ping_(0) $ping_(3)
$ns_ connect $ping_(0) $ping_(9)
#Schedule events
$ns_ at 299.3 "$ping_(0) send1"

$ns_ connect $ping_(3) $ping_(0)
$ns_ connect $ping_(3) $ping_(9)
#Schedule events
$ns_ at 299.3 "$ping_(3) send1"

$ns_ connect $ping_(9) $ping_(0)
$ns_ connect $ping_(9) $ping_(3)
#Schedule events
$ns_ at 299.3 "$ping_(9) send1"

# CH to CM

#Schedule events
$ns_ at 299.5 "$ping_(0) send2"
$ns_ at 299.5 "$ping_(3) send2"
$ns_ at 299.5 "$ping_(9) send2"

# CH to CH

$ns_ connect $ping_(0) $ping_(3)
$ns_ connect $ping_(0) $ping_(9)
#Schedule events
$ns_ at 299.5 "$ping_(0) send3"

$ns_ connect $ping_(3) $ping_(0)
$ns_ connect $ping_(3) $ping_(9)
#Schedule events
$ns_ at 299.5 "$ping_(3) send3"

$ns_ connect $ping_(9) $ping_(0)
$ns_ connect $ping_(9) $ping_(3)
#Schedule events
$ns_ at 299.5 "$ping_(9) send3"

# CH to CM

#Schedule events
$ns_ at 299.7 "$ping_(0) send4"
$ns_ at 299.7 "$ping_(3) send4"
$ns_ at 299.7 "$ping_(9) send4"

# At 399 Sec.

# CM to CH

set ping_(0) [new Agent/Ping]
$ns_ attach-agent $node_(0) $ping_(0)
set ping_(1) [new Agent/Ping]
$ns_ attach-agent $node_(1) $ping_(1)
#Connect the two agents
$ns_ connect $ping_(0) $ping_(1)
#Schedule events
$ns_ at 399.0 "$ping_(1) send"

set ping_(5) [new Agent/Ping]
$ns_ attach-agent $node_(5) $ping_(5)
#Connect the two agents
$ns_ connect $ping_(5) $ping_(0)
#Schedule events

```

```

$ns_ at 399.0 "$ping_(5) send"

set ping_(2) [new Agent/Ping]
$ns_ attach-agent $node_(2) $ping_(2)
#Connect the two agents
$ns_ connect $ping_(2) $ping_(0)
#Schedule events
$ns_ at 399.0 "$ping_(2) send"

set ping_(3) [new Agent/Ping]
$ns_ attach-agent $node_(3) $ping_(3)
set ping_(4) [new Agent/Ping]
$ns_ attach-agent $node_(4) $ping_(4)
#Connect the two agents
$ns_ connect $ping_(4) $ping_(3)
#Schedule events
$ns_ at 399.0 "$ping_(4) send"

set ping_(6) [new Agent/Ping]
$ns_ attach-agent $node_(6) $ping_(6)
#Connect the two agents
$ns_ connect $ping_(6) $ping_(3)
#Schedule events
$ns_ at 399.0 "$ping_(6) send"

set ping_(7) [new Agent/Ping]
$ns_ attach-agent $node_(7) $ping_(7)
#Connect the two agents
$ns_ connect $ping_(7) $ping_(3)
#Schedule events
$ns_ at 399.0 "$ping_(7) send"

set ping_(8) [new Agent/Ping]
$ns_ attach-agent $node_(8) $ping_(8)
#Connect the two agents
$ns_ connect $ping_(8) $ping_(3)
#Schedule events
$ns_ at 399.0 "$ping_(8) send"

set ping_(9) [new Agent/Ping]
$ns_ attach-agent $node_(9) $ping_(9)
set ping_(10) [new Agent/Ping]
$ns_ attach-agent $node_(10) $ping_(10)
#Connect the two agents
$ns_ connect $ping_(10) $ping_(9)
#Schedule events
$ns_ at 399.0 "$ping_(10) send"

set ping_(11) [new Agent/Ping]
$ns_ attach-agent $node_(11) $ping_(11)
#Connect the two agents
$ns_ connect $ping_(11) $ping_(9)
#Schedule events
$ns_ at 399.0 "$ping_(11) send"

set ping_(12) [new Agent/Ping]
$ns_ attach-agent $node_(12) $ping_(12)
#Connect the two agents
$ns_ connect $ping_(12) $ping_(9)
#Schedule events
$ns_ at 399.0 "$ping_(12) send"

set ping_(13) [new Agent/Ping]
$ns_ attach-agent $node_(13) $ping_(13)
#Connect the two agents
$ns_ connect $ping_(13) $ping_(9)
#Schedule events
$ns_ at 399.0 "$ping_(13) send"

# CH to CH

```

```

$ns_connect $ping_(0) $ping_(3)
$ns_connect $ping_(0) $ping_(9)
#Schedule events
$ns_ at 399.3 "$ping_(0) send1"

$ns_connect $ping_(3) $ping_(0)
$ns_connect $ping_(3) $ping_(9)
#Schedule events
$ns_ at 399.3 "$ping_(3) send1"

$ns_connect $ping_(9) $ping_(0)
$ns_connect $ping_(9) $ping_(3)
#Schedule events
$ns_ at 399.3 "$ping_(9) send1"

# CH to CM

#Schedule events
$ns_ at 399.5 "$ping_(0) send2"
$ns_ at 399.5 "$ping_(3) send2"
$ns_ at 399.5 "$ping_(9) send2"

# CH to CH

$ns_connect $ping_(0) $ping_(3)
$ns_connect $ping_(0) $ping_(9)
#Schedule events
$ns_ at 399.5 "$ping_(0) send3"

$ns_connect $ping_(3) $ping_(0)
$ns_connect $ping_(3) $ping_(9)
#Schedule events
$ns_ at 399.5 "$ping_(3) send3"

$ns_connect $ping_(9) $ping_(0)
$ns_connect $ping_(9) $ping_(3)
#Schedule events
$ns_ at 399.5 "$ping_(9) send3"

# CH to CM

#Schedule events
$ns_ at 399.7 "$ping_(0) send4"
$ns_ at 399.7 "$ping_(3) send4"
$ns_ at 399.7 "$ping_(9) send4"

# At 499 Sec.

# CM to CH

set ping_(0) [new Agent/Ping]
$ns_attach-agent $node_(0) $ping_(0)
set ping_(1) [new Agent/Ping]
$ns_attach-agent $node_(1) $ping_(1)
#Connect the two agents
$ns_connect $ping_(0) $ping_(1)
#Schedule events
$ns_ at 499.0 "$ping_(1) send"

set ping_(5) [new Agent/Ping]
$ns_attach-agent $node_(5) $ping_(5)
#Connect the two agents
$ns_connect $ping_(5) $ping_(0)
#Schedule events
$ns_ at 499.0 "$ping_(5) send"

set ping_(2) [new Agent/Ping]
$ns_attach-agent $node_(2) $ping_(2)

```

```

#Connect the two agents
$ns_connect $ping_(2) $ping_(0)
#Schedule events
$ns_ at 499.0 "$ping_(2) send"

set ping_(3) [new Agent/Ping]
$ns_attach-agent $node_(3) $ping_(3)
set ping_(4) [new Agent/Ping]
$ns_attach-agent $node_(4) $ping_(4)
#Connect the two agents
$ns_connect $ping_(4) $ping_(3)
#Schedule events
$ns_ at 499.0 "$ping_(4) send"

set ping_(6) [new Agent/Ping]
$ns_attach-agent $node_(6) $ping_(6)
#Connect the two agents
$ns_connect $ping_(6) $ping_(3)
#Schedule events
$ns_ at 499.0 "$ping_(6) send"

set ping_(7) [new Agent/Ping]
$ns_attach-agent $node_(7) $ping_(7)
#Connect the two agents
$ns_connect $ping_(7) $ping_(3)
#Schedule events
$ns_ at 499.0 "$ping_(7) send"

set ping_(8) [new Agent/Ping]
$ns_attach-agent $node_(8) $ping_(8)
#Connect the two agents
$ns_connect $ping_(8) $ping_(3)
#Schedule events
$ns_ at 499.0 "$ping_(8) send"

set ping_(9) [new Agent/Ping]
$ns_attach-agent $node_(9) $ping_(9)
set ping_(10) [new Agent/Ping]
$ns_attach-agent $node_(10) $ping_(10)
#Connect the two agents
$ns_connect $ping_(10) $ping_(9)
#Schedule events
$ns_ at 499.0 "$ping_(10) send"

set ping_(11) [new Agent/Ping]
$ns_attach-agent $node_(11) $ping_(11)
#Connect the two agents
$ns_connect $ping_(11) $ping_(9)
#Schedule events
$ns_ at 499.0 "$ping_(11) send"

set ping_(12) [new Agent/Ping]
$ns_attach-agent $node_(12) $ping_(12)
#Connect the two agents
$ns_connect $ping_(12) $ping_(9)
#Schedule events
$ns_ at 499.0 "$ping_(12) send"

set ping_(13) [new Agent/Ping]
$ns_attach-agent $node_(13) $ping_(13)
#Connect the two agents
$ns_connect $ping_(13) $ping_(9)
#Schedule events
$ns_ at 499.0 "$ping_(13) send"

# CH to CH

$ns_connect $ping_(0) $ping_(3)
$ns_connect $ping_(0) $ping_(9)
#Schedule events

```

```

$ns_ at 499.3 "$ping_(0) send1"

$ns_ connect $ping_(3) $ping_(0)
$ns_ connect $ping_(3) $ping_(9)
#Schedule events
$ns_ at 499.3 "$ping_(3) send1"

$ns_ connect $ping_(9) $ping_(0)
$ns_ connect $ping_(9) $ping_(3)
#Schedule events
$ns_ at 499.3 "$ping_(9) send1"

# CH to CM

#Schedule events
$ns_ at 499.5 "$ping_(0) send2"
$ns_ at 499.5 "$ping_(3) send2"
$ns_ at 499.5 "$ping_(9) send2"

# CH to CH

$ns_ connect $ping_(0) $ping_(3)
$ns_ connect $ping_(0) $ping_(9)
#Schedule events
$ns_ at 499.5 "$ping_(0) send3"

$ns_ connect $ping_(3) $ping_(0)
$ns_ connect $ping_(3) $ping_(9)
#Schedule events
$ns_ at 499.5 "$ping_(3) send3"

$ns_ connect $ping_(9) $ping_(0)
$ns_ connect $ping_(9) $ping_(3)
#Schedule events
$ns_ at 499.5 "$ping_(9) send3"

# CH to CM

#Schedule events
$ns_ at 499.7 "$ping_(0) send4"
$ns_ at 499.7 "$ping_(3) send4"
$ns_ at 499.7 "$ping_(9) send4"

# Define scenario model

puts "Loading scenario file..."
source $val(sc)

# Define node initial position in nam

for {set i 0} {$i < $val(nn)} {incr i} {

    # 20 defines the node size in nam, must adjust it
    # according to your scenario
    # The function must be called after mobility model is
    # defined

    $ns_ initial_node_pos $node_($i) 20
}

# Tell nodes when the simulation ends

for {set i 0} {$i < $val(nn)} {incr i} {
    $ns_ at $val(stop).0 "$node_($i) reset";
}

$ns_ at $val(stop).0001 "stop"
$ns_ at $val(stop).0002 "puts \"NS EXITING...\" ;
$ns_ halt"

puts $tracefd "M 0.0 nn $val(nn) x $val(x) y $val(y) rp
$val(adhocRouting)"
puts $tracefd "M 0.0 sc $val(sc) cp $val(cp) seed
$val(seed)"
puts $tracefd "M 0.0 prop $val(prop) ant $val(ant)"

proc stop {} {
    global ns_ namtrace tracefd
    $ns_ flush-trace
    close $tracefd
    close $namtrace
}

#Run the simulation
$ns_ run

```

4. Running the simulation

- (1) Before running the simulation, we should make some necessary modification according to the requirements of the *aodv* files, *ping* files, and *ip* files (Figure C.2). Then, copy the related files to the correct folders: *aodv.h* and *aodv.cc* to *ns/ns-allinone-2.28/ns-2.28/aodv*, *ping.h* and *ping.cc* to *ns/ns-allinone-2.28/ns-2.28/apps*, *ip.h* and *ip.cc* to *ns/ns-allinone-2.28/ns-2.28/common*.
- (2) Generate the corresponding scenario file in the directory *ns/ns-allinone-2.28/ns-2.28/indep-utils/cmu-scen-gen/setdest*, and type the command “./setdest -V1 -n (how many nodes) -p (pause time) -M (node speed) -t (simulation time) -x (length of the simulation area) -y (width of the simulation area) > scenario file name. Then make the necessary modification according to requirements (Figure C.3). Finally, copy the scenario file to the folder where the user will run the simulation.

- (3) At ns/ns-allinone-2.28/ns-2.28, retype the command “./configure” and “make”.
- (4) Copy the tcl file to the folder that the user will run the simulation (Figure C.4). At ns/ns-allinone-2.28/ns-2.28, type the command “ns *.tcl” to run the simulation.
- (5) Some new files named *.nam and *.tr will be generated in the folder.
- (6) At ns/ns-allinone-2.28/ns-2.28, type the command “awk -f cache_manet.awk *.tr” to get the results of the simulation (Figure C.5).
- (7) At ns/ns-allinone-2.28/ns-2.28, type the command “nam *.nam” to play the animation of the whole simulation (Figure C.6).

```

[antony@localhost ~]$ dir
BackupNSALL clusterest d Debug Desktop hpux ns
[antony@localhost ~]$ cd clusterest/
[antony@localhost clusterest]$ dir
gifmerge-1.33-src-10.10.tar.gz test01
[antony@localhost clusterest]$ cd test01/
[antony@localhost test01]$ dir
cache-manet.awk replication14100.tcl wireless\ range
default-scene-14-cluster replication14.nam
output2 replication14.tr
[antony@localhost test01]$ nam replication14.nam
[antony@localhost test01]$

```

Figure C.1 Simulation Terminal

```

int hdr_aodv::offset_;
static class AODVHeaderClass : public PacketHeaderClass {
public:
    AODVHeaderClass() : PacketHeaderClass("PacketHeader/AODV",
                                           sizeof(hdr_all_aodv)) {
        bind_offset(&hdr_aodv::offset_);
    }
} class_rtProtoAODV_hdr;

static class AODVclass : public TclClass {
public:
    AODVclass() : TclClass("Agent/AODV") {}
    TclObject* create(int argc, count char*const* argv) {
        assert(argc == 5);
        //return (new AODV((nsaddr_t) atoi(argv[4])));
        return (new AODV((nsaddr_t) Address::instance().str2addr(argv
[4])));

```

Figure C.2 AODV Routing Protocol

```

$ns_ at 31.756015300670 "$sod_ set-dist 6 12 1"
$ns_ at 32.762148083490 "$sod_ set-dist 2 7 1"
$ns_ at 37.209141265599 "$node_(13) setdest 144.659654327950
193.361478582767 0.000000000000"
$ns_ at 38.962278732476 "$sod_ set-dist 3 12 2"
$ns_ at 39.209141265599 "$node_(13) setdest 96.559215100556 154.785879607187
0.264435741818"
$ns_ at 39.353463814606 "$node_(10) setdest 40.690131756372 229.022743049248
0.000000000000"
$ns_ at 41.353463814606 "$node_(10) setdest 166.362895445459 29.025953737413
0.750444449040"
$ns_ at 43.253023738013 "$node_(0) setdest 195.318634077080 282.713530795745
0.000000000000"
$ns_ at 44.486703812758 "$sod_ set-dist 5 11 1"
$ns_ at 44.55458712345 "$sod_ set-dist 6 8 1"
$ns_ at 44.604923966924 "$node_(3) setdest 178.545725144798 5.995385150202
0.000000000000"
$ns_ at 45.253023738013 "$node_(0) setdest 121.355019835950 219.470430759212
1.443604526638"
$ns_ at 45.981658873994 "$sod_ set-dist 4 10 1"

```

Figure C.3 Simulation Scenario

```

set val(prop) Propagation/TwoRayGround
set val(netif) Phy/WirelessPhy
set val(mac) Mac/802_11
set val(ifq) Queue/DropTail/PriQueue
set val(ll) LL
set val(ant) Antenna/OmniAntenna
set val(x) 300 ;# X dimension of the topography
set val(y) 300 ;# Y dimension of the topography
set val(ifqlen) 100 ;# max packet in ifq
set val(seed) 0.0
set val(adhocRouting) AODV
set val(nn) 14 ;# how many nodes are simulated
set val(cp) 1
set val(ac) "/default-scene-14-cluster"
set val(stop) 500.0 ;# simulation time

# Main Program

```

Figure C.4 Simulation Program

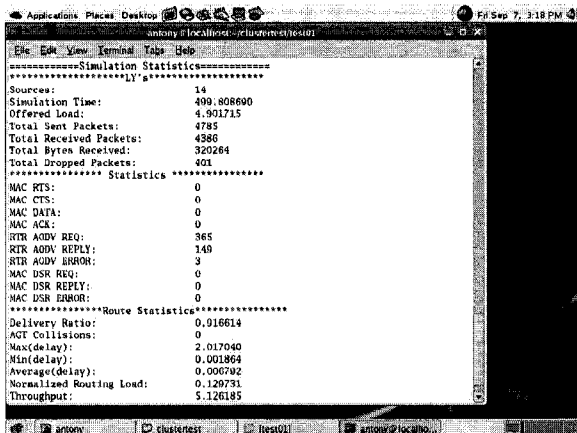


Figure C.5 Simulation Result

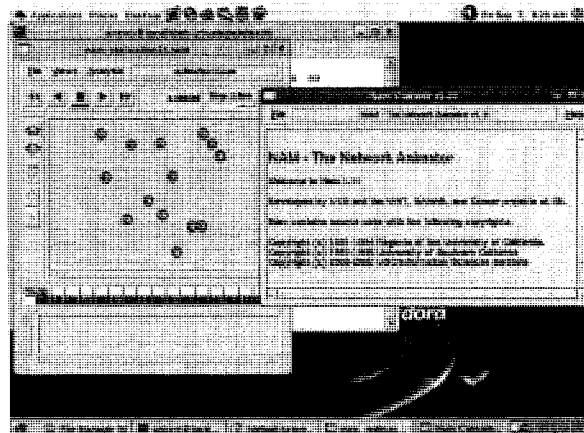


Figure C.6 NAM

PPENDIX D: LIST OF PUBLICATIONS

Yang, L. and Hammad, A. (2007). “Ad-hoc Wireless Networking for Supporting Communication and On-Site Data Collection”, ASCE Workshop on Computing in Civil Engineering 2007, July 2007, Pittsburgh, PA, U.S.A. 854-861.